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BuAer Report AE-61-4

Fundamentals of Design of Piloted
Aircraft Flight Control Systems

Volume III

THE HUMAN PILOT

PUBLISHED BY DIRECTION OF
THE CHIEF OF THE BUREAU OF AERONAUTICS

IMPORTANT NOTE

This volume was written by and for engineers and scientists who are concerned with the analysis and synthesis of piloted aircraft flight control systems. The Bureau of Aeronautics undertook the sponsorship of this project when it became apparent that many significant advances were being made in this extremely technical field and that the presentation and dissemination of information concerning such advances would be of benefit to the Services, to the airframe companies, and to the individuals concerned.

A contract for collecting, codifying, and presenting this scattered material was awarded to Northrop Aircraft, Inc., and the present basic volume represents the results of these efforts.

The need for such a volume as this is obvious to those working in the field. It is equally apparent that the rapid changes and refinements in the techniques used make it essential that new material be added as it becomes available. The best way of maintaining and improving the usefulness of this volume is therefore by frequent revisions to keep it as complete and as up-to-date as possible.

For these reasons, the Bureau of Aeronautics solicits suggestions for revisions and additions from those who make use of the volume. In some cases, these suggestions might be simply that the wording of a paragraph be changed for clarification; in other cases, whole sections outlining new techniques might be submitted.

Each suggestion will be acknowledged and will receive careful study.

For those which are approved, revision pages will be prepared and distributed. Each of these will contain notation as necessary to give full credit to the person and organization responsible.

This cooperation on the part of the readers of this volume is vital. Suggestions forwarded to the Chief, Bureau of Aeronautics (Attention AE-612), Washington 25, D. C., will be most welcome.

L. M. Chatter
Head, Actuating & Flight Controls Systems Section
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PREFACE

This volume has been written under BuAer Contract NOas 51-514(c) to make available to engineers concerned with the design of integrated aircraft control systems certain basic information about the human pilot.

The entire volume is a codification of material which is available in textbooks, periodicals, and numerous reports of various government agencies and corporations. The very diversity of these sources and their differing degrees of dissemination to interested engineers are the principal reasons why it is hoped that a coherent compilation, such as this volume claims to be, will be useful.

The codification was made under the restriction that the volume is intended for systems engineers, and is meant to provide them with basic knowledge concerning those aspects of dynamic responses directly relevant to the design of aircraft control systems. Specifically, many matters of great importance to the psychologist or physiologist are omitted, and to them the material of Chapter II will be elementary.

Under that restriction, then, it has been convenient to divide the subject matter into two broad parts: The first category, which includes the contents of Chapter II, is concerned with the mechanism by which a pilot senses stimuli and actuates controls, and with the quantitative dynamic properties of this mechanism, such as thresholds of perception, limits to forces which can be applied, reaction-time

delays, etc. The second category, treated in Chapter III, describes the results of recent attempts to develop mathematical models or network analogies of the human pilot which systems engineers can use, according to existing techniques, to predict the responses made by pilots in controlling an airplane.

Many individuals, agencies, and companies have provided the sources for the material of this volume, as the extensive bibliography shows. Two of these sources were so heavily relied upon that special mention of them must be made here. They are the Tufts College Handbook of Human Engineering Data, prepared under an ONR contract for the Special Devices Center by the Tufts College Institute for Applied Experimental Psychology, and secondly, the several reports of studies made at Goodyear Aircraft, Inc., under the direction of Robert R. Mayne.

Special mention should also be made of F. B. Bacus, who coordinated the reproduction and prepared the figures and equations; of Virginia Dempsey, who prepared the tables; and of Edna Garcia, who typed the text.

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CHAPTER I

INTRODUCTION

This volume is intended to serve two purposes. The first of these is to provide engineers who are responsible for the synthesis of flight control systems for piloted aircraft with a quantitative description of the characteristics of a human pilot viewed as a sensor and as an actuator. Chapter II contains experimental data concerning (1) the accuracy of the pilot's senses, (2) the maximum forces which a pilot can exert as well as the accuracy with which he can exert these forces, and (3) the pilot's reaction-time delays between stimulus and response.

The second aim is twofold: (1) to present the approximate transfer functions which have been recently developed to describe human pilots engaged in simple tasks, and (2) to present the methods for simulating on an analog computer a pilot in a routine flying situation. This material is contained in Chapter III.

Since the volume is written to fill the needs of flight control system engineers, it is presumed that transfer functions are a familiar concept and that the techniques for using them, as well as analog computers, in system synthesis are understood. Therefore, these concepts and techniques are not discussed. Readers to whom they are unfamiliar are referred to Methods of Analysis and Synthesis of Piloted Aircraft Flight.

Control Systems, written by personnel of the Servomechanisms Department of Northrop Aircraft, Inc.,* or to Theory of Servomechanisms, by James, Nichols, and Phillips (Reference 15).

It must be emphasized that this volume does not include the results of original research carried out by the author. Its contents are already familiar to specialists in various fields, for it contains only the results of investigations previously conducted and reported by others. This is in agreement with the purpose of presenting a systematic, unified, exposition of relevant data to engineers occupied with the design of flight control systems. It has been felt that although much information is available, it is scattered throughout so many different references, some of which are certainly not readily available to an interested engineer, that a definite need exists for a collection of such data in a single volume, edited specifically for flight control system designers. This volume claims to meet this need only.

Since this volume is written for designers of flight control systems, attention is focussed on a normal pilot in a normal flying environment, and further, it is assumed that the cockpit and instruments have been so designed that pilot performance will be as efficient as possible. As a result, two important fields of research on human pilots are neglected. The first includes the physiology of flight and aviation medicine, both concerned with the causes and prevention of factors leading to decreased performance by pilots of modern airplanes and with providing adequate safety measures for emergency conditions

* BuAer Report AE-61-4 I, 1952.

of flight. The ever-increasing demands made on pilots by greater speeds and altitudes and the physiological limits to such demands mean that aviation medicine has huge tasks confronting it. Fortunately, that science is very active, and its findings are readily available. Consequently, the engineer who needs information about the possibilities of environment alteration for the sake of pilot protection can turn to many sources.

The second field neglected here is that of Human Engineering. The assumption made above that cockpit and instruments are properly designed depends for its justification on the success of efforts in Human Engineering, which deals with such considerations as the position, lettering, and alignment of instrument dials, cockpit illumination, seating facilities, and the shape and location of control handles. Well-organized presentations of the results of these considerations are found in References 10 and 20.

The two principal functions of a flight control system for a piloted aircraft are (1) to enable the pilot to maintain the airplane in a desired flight condition despite transient disturbances, such as gusts, and (2) to enable him to command changes in the aircraft's orientation when needed. The former function deals with the stability of the airplane, and the latter with its control. In synthesizing or analyzing a flight control system, the engineer must be concerned with the stability and control of the over-all system which consists of the following subsystems: the airframe itself, the control surfaces and their actuators, the engine and throttle, the human

pilot, and finally, in the case of modern, high performance craft, one or more auxiliary systems. These auxiliary systems are of two kinds: (1) automatic stability augmenters, which operate independently of the pilot to maintain zero deviation from a specified flight path when this is needed (as it is, for instance, in bombing), and (2) artificial feel systems which provide the pilot with the necessary control feel for flying when the control surfaces are power-boosted or fully power-operated.

Usually the designer seeks to alter the characteristics of the auxiliary systems, the actuating system, and perhaps even the control surfaces themselves, so that the stability and control properties of the entire system, including the airframe and the pilot as unalterable elements, will be satisfactory.

The flight control system engineer must predict what these properties of the complete system will be when the aircraft is actually flown. A laboratory mockup might be built, with which experiments could be run simulating actual flight conditions. This is obviously a costly and time-consuming method. It would be better to have a mathematical model of each of the component subsystems and a mathematical technique for deriving from these models the over-all response of the complete system.

Clearly, the validity of predictions based on such a mathematical model of the system depends on the accuracy with which the models simulate the subsystems as well as on the applicability of the analytical technique used.

In order to develop reliable models of the subsystems, detailed knowledge of the performance characteristics of these subsystems must be available for the range of flight conditions which will be encountered. For most of the subsystems, there is a large body of such data, and satisfactory mathematical models have been developed through years of continuing research and the accumulation of experience. Other volumes prepared by this contractor have dealt specifically and in detail with the dynamics of the airframe, the hydraulic system, the artificial feel system, and the autopilot. Some of this information is available in other sources. The result is that the flight control systems designer has much information available on these subsystems and well-defined techniques for obtaining additional knowledge if needed.

Furthermore, the use of the Laplace transform and analog computers according to methods used in servomechanism theory (see Reference 15) provides an analytical technique for predicting the response of the entire airframe system when the open loop transfer functions of all the component subsystems are known.

When an engineer seeks to simulate the complicated subsystem consisting of the human pilot himself, he is not so fortunate. Only recently, and only by a few investigators, has serious attention been given to an attempt to develop a mathematical model which would describe a trained pilot flying an airplane and which would be suitable for operational and

computer analysis. Consequently, the synthesis and analysis of flight control systems have usually been approached by studying the closed loop response of the airframe without including the pilot in the loop. But since one of the most important subsystems was therefore omitted, a definite limit was placed upon the accuracy of the analysis and upon the validity of the synthesis. Some attempt to compensate for this omission was made later during flight-testing by interviewing the pilots for their opinions concerning the stability and controllability of the airplane, but pilots often do not agree in their evaluation of the flight characteristics of the same plane, and moreover, as Orlansky states, "Pilots have often endured undesirable practices without complaint" (quoted in Reference 10). However, in the absence of a suitable mathematical representation of the pilot, the designer had no other recourse.

Thus the engineer responsible for designing a flight control system needs a method of representing a pilot in the activity of controlling an airplane. An explicit transfer function, linear, or nonlinear due to reaction-time delay, would be ideal, for it could be readily used with well-known, relatively simple, mathematical techniques of closed loop synthesis and analysis. In cases where such an explicit function cannot be used, a network for simulating important features of the pilot's response on an analog computer would be entirely satisfactory if it were a faithful representation. Such a network could easily simulate certain nonlinearities of human response, such as reaction time, thresholds of perception, and limited outputs, all of which must be taken into account regardless of whether any other simplifying

assumptions are used. It should be noted that such mathematical models are not intended to describe higher-level functions of the pilot, such as decision-making, and cannot be expected to; they can only describe his performance of a task which he has previously learned by training. Further, experimental evidence shows that no single transfer function or electric analog can be a good approximation to all the responses made by a human pilot. Nonetheless, it may be possible to approximate different responses by different transfer functions or analogs. Although this variation of transfer functions is philosophically unsatisfying, it is not inherently unacceptable. Indeed, every transfer function used in the entire airplane system is at best only a good approximation for a limited range of conditions. It therefore seems reasonable, at least to attempt to formulate pilot transfer functions which are representative enough for the perturbation studies which are usually relied on in stability and control investigations. Several such functions and at least one network analog have been developed which are applicable to specific situations. Proper use of them can mean a more accurate synthesis, but of course improper use must be avoided.

To use mathematical models of the pilot's response intelligently, the designer must have: (1) a clear understanding of what a pilot does in flying and (2) a description, as precise and as quantitative as possible, of the way he performs these functions. Moreover, such information is extremely useful in itself. For instance, in airplanes with

a fully-powered control system, an artificial feel system is required. Obviously, a prerequisite to its design is the knowledge of what constitutes satisfactory feel characteristics, and this can only be obtained by knowing what cues the pilot uses in flying as well as the nature of the senses he uses in detecting them.

When controlling an airplane, a human being acts both as a sensor of the craft's deviations from a desired flight condition and as an actuator of the aircraft's controls. In the latter role, the pilot may or may not be called upon to supply all the power needed to move the control surfaces. In any case, he must always exert a pressure to deflect a stick, wheel, or pedal, and in this sense he is a force-producer and acts like an actuator.

Thus, an accurate description of the performance of a human pilot can be separated into describing him in terms of a sensor and an actuator. To understand him as a sensor requires answers to such questions as: What senses are used in flying? What is the precision of each of these senses? What are the threshold values of the errors which can be detected by these senses? To understand the pilot as an actuator, certain other questions must be answered. Among these are: What are the upper limits to forces pilots can exert? How accurately can the pilot exert pressure to displace controls? In addition, information concerning the reaction-time delays between stimulus and response must be known.

In recent years, more and more research has been undertaken to answer these and similar questions. So far, the results are not nearly so reliable as the corresponding information concerning other subsystems of piloted aircraft. But it is clear that these results should be readily available to designers who are responsible for flight control systems, and this information forms the content of Chapter II.

In a book of this sort, in which the content depends chiefly upon the work of others, documentation is important, both as a means of directing interested readers to the original sources which may present more detailed information, and also as an implicit expression of this author's indebtedness to the scientists whose efforts have made the included data available. Therefore, numerous references are made throughout the text when experimental results are mentioned, and a selected bibliography is appended.

CHAPTER II

FUNDAMENTAL ASPECTS OF THE SENSING AND ACTUATING PROCESSES OF A HUMAN PILOT

SECTION 1 - INTRODUCTION

This chapter presents a summary of the available physiological and psychological information concerning a normal human-being regarded as a sensor and as an actuator. The general information presented can be found in numerous textbooks and is offered here only to supply useful background material to aircraft designers who need such information in their work. The detailed numerical data were culled from several sources, but primarily from two editions of the Tufts College Handbook of Human Engineering Data (References 10 and 10*), which make up an encyclopedia of data obtained from numerous experiments by many research workers. Another important source was Orlansky's monograph The Human Factor in the Design of Stick and Rudder Controls (Reference 23).

The chapter is divided into three parts: Section 2 is a summary of information relating to the nature and operation of the human sensory-motor system, as understood today. Section 3 deals specifically with the following senses, which are of primary importance to the pilot: (1) the visual sense, (2) the vestibular senses, and (3) the proprioceptive and tactual senses. Each is treated in as much detail as the scope of the volume permitted; the best quantitative information available on such matters as thresholds of perception and thresholds of discrimination is

Section 2

included. Section 4 is a discussion of those aspects of the motor system which are of chief concern to the pilot. Considering the pilot as an actuator, relevant data pertaining to his performance as a force producer and as a motion producer are presented. Finally, numerical values for the reaction times which occur in motor responses are given, in an order designed to illustrate the variables which affect these reaction times.

SECTION 2 - GENERAL SENSORY AND MOTOR INFORMATION

The complex mechanism which enables a human being to control an airplane contains approximately one hundred million units. Each of these units consists of a receptor, an effector, and a connector. The receptors make it possible for the pilot, either directly or with the aid of instruments, to perceive the orientation of the airplane with respect to the environment and to detect changes in this relationship. The effectors provide the means by which the data from the receptors, after suitable correlation and integration, result in the appropriate response. The function of the connectors is not only to transmit data from receptor to effector but also to effect the correlation, integration, and discrimination necessary for preventing chaotic activity and for providing orderly responses to the numerous stimuli constantly bombarding the pilot.

The function of the receptors, which are either simple nerve endings or specialized cells associated with nerve endings, is to produce a nervous impulse in the associated nerve. To do this, the receptor must be activated by the stimulus to which it is specifically adapted. Generally, the receptors are found

Section 2

in an end-organ, which may be very complex or extremely rudimentary. For example, the end-organ for the visual sense is the complicated mechanism of the eye; the end-organ for some of the tactual senses, however, is simply a bulb of tissue surrounding the nerve endings. The function of the end-organs is to receive stimuli from the environment and to transmit them in a useful form to the receptors, as the eye serves to focus the light rays which are the specific stimuli for the visual sense.

The receptors which will be treated in detail in the following pages are those for the visual, vestibular, and proprioceptive senses.

EFFECTORS

There are three types of effectors in a human body: the striated muscles (so-called because of their appearance), the smooth muscles, and the endocrine glands. The latter two types automatically and involuntarily effect the responses required to regulate those continuing body activities which are associated with life, such as breathing and digestion. Naturally they play a vital role in maintaining the pilot's efficiency despite physical changes in the environment; the responses which are made to stimuli such as fatigue, fear, hunger, or hypoxia, to name a few, radically alter the characteristics of the pilot. One result of the restriction of the content of this volume to a consideration of a normal pilot in a normal environment is that the responses of endocrine and smooth muscle effectors are omitted since it is assumed that they serve to keep the pilot's acumen at the highest possible level.

Section 2

The other system of effectors, the striated muscles, is often referred to as the skeletal system because these muscles are attached to bony parts of the body by means of tendons. It is this system which produces movement of various body members and thus enables the pilot to actuate airplane controls.

Every muscle of the skeletal system is made up of a large number of fibers connected by tissue; these give the striated appearance. To each of these fibers are attached nerve endings, some of which bring nervous impulses to the fiber, causing it to contract, whereas others are really rudimentary end-organ receptors of the proprioceptive senses and are stimulated by contraction of the fiber. These are the receptors which must provide the feedback for closed loop control of voluntary muscular action.

An important characteristic of the response of the fiber is its "on-off" behavior: a fiber is either shortened as much as possible or not at all; in response to a nervous impulse above a certain intensity, the fiber contracts, but in the absence of such an impulse, it is relaxed. At any instant, some of the fibers in a living muscle are contracted; the over-all tension of a muscle depends upon how many fibers are shortened. Since different groups of fibers in a given muscle have different threshold levels at which they contract, the tension of the muscle increases by steps rather than continuously even though the intensity of the stimulus increases continuously. The apparent continuity which is felt as a muscle tightens is due to the very small step increments resulting from the very large number of fiber groups having slightly different

Section 2

threshold levels; in addition, there is the "smoothing" effect of the connecting tissue between the individual fibers.

Another significant property of muscle action is the so-called refractory phase. After a muscle has responded to a stimulus by increasing or decreasing its tension, a certain period of time must elapse before it can respond to a second stimulus. This interval is referred to as the refractory phase; its duration varies from muscle to muscle but is generally of only a few milliseconds. Actually, the refractory phase must be divided into two different periods: the absolute refractory phase and the relative refractory phase. During the first of these, the muscle cannot react to any stimulus, no matter how large; during the second, the muscle can react only to stimuli of unusually high intensity. Furthermore, immediately following the refractory phase, there is a period of increased responsiveness (hyperexcitability) during which the muscle reacts to stimuli of an intensity below its usual threshold level.

The phenomena of "on-off" muscle action and the refractory phase make it clear that the response of a human operator is, in the last analysis not only a nonlinear but also a discontinuous function of the stimulus. The assumption of linearity in predicting a response must therefore be justified by experiments which show that the nonlinearities and discontinuities produce deviations which are negligible for the purpose at hand.

Section 2

The muscles of the skeletal system always exist in pairs: for every muscle which by its contraction moves a member of the body in a certain direction, there is another muscle whose contraction moves that member in the opposite direction. These opposing sets of muscles, attached to the same member, are called agonists and antagonists. When both sets of muscles are contracted as much as possible, the member is rigidly fixed. Movement of a hand or a leg, for instance, requires not only the partial contraction of the agonists, but also the partial relaxation of the antagonists. This relaxation is provided automatically by the central nervous system once the motion has been learned; facility can be improved by training.

In a slow, reciprocating movement, both the agonists and antagonists are in constant partial tension, which Stetson (quoted in Reference 2) calls a muscle fixation. According to Bates (in the same reference), as the speed of movement is increased to approximately two cycles per second, the periods of tension in opposing groups overlap less and less until at resonance they do not overlap at all. The resulting motion is called a ballistic movement. The difference between the two, in the performance of a motion requiring skill, can be easily understood by comparing the jerky, slow penmanship of a child learning to write, who uses a muscle fixation because he cannot properly relax the antagonists, with the mature penmanship of an adult, who makes more use of ballistic movement. Indeed, as Stetson says, it seems that the key to acquiring speed, skill, and accuracy in activities involving motion is the replacement of muscle fixation by ballistic movement through training and practice. After such training, the central nervous system will automatically provide the necessary relaxation of the antagonists.

Section 2

Bates further observes that increasing the frequency of a reciprocating movement beyond the natural frequency of two cycles per second causes the amplitude to decrease until it reaches zero at approximately eight to ten cycles per second for all body members.

CONNECTORS

As mentioned above, the fundamental function of the connectors is to transmit to an effector the nervous impulses produced in a nerve-ending by the end-organ of a receptor. Since the only effectors treated here are the striated muscles, the only connectors of interest are those which end at fibers of such muscles. The central nervous system, which is interposed between the receptors and the effectors, serves the functions of collecting and integrating impulses from the receptors, mediating them according to conscious plans of activity (if any), and distributing them to the proper channels to evoke desired responses. In addition, this system can initiate impulses directed to the effectors to produce movement called for by the higher levels of the brain.

The central nervous system includes the spinal cord, the autonomous nervous system, and the following parts of the brain itself: the medulla, the pons and cerebellum, the midbrain and thalamus, and the cerebrum. However, since the autonomous nervous system does not exert any direct regulation on the skeletal system, no further mention of it will be made.

Section 2

The various nerves of the body can be conveniently classified according to their functions: (1) afferent nerves are those which transmit impulses from the receptors to the central nervous system (these are also called sensory nerves), (2) efferent nerves are those which transmit impulses from the central nervous system to the effectors, and (3) connecting nerves are those which transmit impulses within the central nervous system. The following paragraphs will briefly describe these nerves and present the best available conception of the nature of nervous impulses.

The basic unit of every nerve is the neurone; the nerve itself consists of a bundle of neurones much as a telephone cable consists of a bundle of conductors. Each neurone is a single cell made up of four parts: (1) the nucleus and surrounding protoplasm, (2) the dendrites, (3) the axon, and (4) the end-brush. The dendrites, which resemble the branches of a tree, issue from that end of the neurone which contains the nucleus; they form the receivers of nervous impulses for the neurone. The rod-like axon transmits impulses from the dendrites to the end-brush at the opposite end of the neurone. The function of the end-brush is to discharge the impulse: in the case of a neurone of a motor nerve, the impulse is discharged either into a muscle fiber or into the dendrites of another neurone leading toward a muscle; in the case of a sensory nerve, the discharge is into the dendrites of another neurone leading to the central nervous system.

Section 2

It is easily verified that an electric current accompanies a nervous impulse along a nerve. It is usually assumed that this current is the nervous impulse. In any event, this current varies in frequency but its magnitude is fixed. The frequency is directly proportional to the intensity of the stimulus. According to Bates (Reference 2), the current is transmitted at frequencies up to 400 cycles per second and can travel along a nerve at rates up to 300 feet per second. An important fact is that under the influence of a constant stimulus, the frequency of a nervous impulse decreases with time. The important conclusion to be drawn is that the sensory system, according to Bates, "has evolved principally to detect changes in environment." In other words, it is a differentiating mechanism. Following a stimulus, neurones, like muscles, exhibit both absolute and relative refractoriness, as well as hyperexcitability.

The neurones, which are the fundamental units of the connecting system, are combined into a complex network of nerves. The connection between nerves in these networks is made at the synapses. Here, the end-brushes of neurones are brought very close to the dendrites of other neurones, but not into contact with them. The synapses provide a very important first stage in the necessary process of sorting and distributing the impulses aroused by stimulation. In the first place, the large number of neurones brought into proximity at a synapse provides a multiplicity of possible interconnections between nerves. Thus it is possible for a single stimulus to be relayed to several different effectors to achieve the desired response, and conversely, stimuli from more than one sensor may reach a single effector.

Section 2

Furthermore, the synapses polarize the travel of impulses; although a dissected nerve can transmit impulses in either direction, it is found that at a synapse, impulses can be transmitted only from the end-brushes to the dendrites.

Finally, the threshold for transmission of an impulse at a synapse is higher than that in the nerve fiber itself; in fact, one function of the synapse is apparently to block stimuli of too little intensity. Moreover, this threshold varies from synapse to synapse, with the result that an impulse reaching a junction and "looking into" the multiple paths open to it, "sees" different resistances. It is presumed that the paths of least resistance are favored, and this preliminary selection begins the process of distributing the impulse properly.

The main channel by which afferent and efferent nerves are connected with the higher centers of the central nervous system is the spinal cord. The spinal cord itself also controls some very simple muscular activities called reflexes. In reflex activities, the receptors and effectors are connected in the spinal cord: no other part of the central nervous system is involved. Examples of such activities are the contraction of the pupil of the eye in response to a bright light, the jerking of a leg when the knee is tapped, or the automatic flexing of one leg when the other is extended in walking. These reflexes have in common the very short time between stimulus and response and their complete independence of conscious control.

Section 2

The other two broad types of muscular activity are characterized by the fact that the interconnection between receptor and effector involves the higher levels of the central nervous system, that is, the brain-stem, the midbrain, and the cerebrum. One of these types is voluntary activity which is at all times under conscious control. The other type is midway between reflex and voluntary activity in the sense that once a decision to act has been made, the response is carried out automatically without conscious control. Examples are throwing a ball and tying a shoe-lace. Activities of this sort must be learned, but once learned, an attempt to exert conscious control may actually impair performance.

The higher levels of the central nervous system include the medulla, the cerebellum, the midbrain, the thalamus, and the cerebrum. The listing is in order of increasing authority; the cerebrum (including the cerebral cortex) dominates all neural functioning. To a certain extent, localization of specific functions in these parts has been made, especially in the cerebrum. It is sufficient for the purposes of this volume to mention again that it is in these centers that the final integration, control, and direction of muscular activity, either by conscious control or by learned and therefore automatic processes, are achieved. Even then, the pattern of stimulus and response is still observed: both conscious control and a decision to activate an automatic muscular movement require stimuli from the environment.

Section 3

SECTION 3 - THE PILOT AS SENSOR

It was mentioned above that the designer of a flight control system is concerned with both the stability and the control of the piloted airframe system. This section is devoted to listing the senses used by a pilot engaged in stabilizing or controlling an airplane, to describing the operation of these senses, and to presenting the available quantitative data concerning their performance. In other words, this section describes the human pilot as a sensor.

Consider the situation where a pilot has trimmed his airplane at a certain airspeed and altitude in a given compass heading with wings level. Assume he is intent on maintaining this flight condition, that is, on stabilizing the system in this flight condition. In order for the craft to deviate from this condition, it must be accelerated. This acceleration may be linear, radial, or angular. Concomitant with any such acceleration, the resultant force on the pilot is altered. This change in resultant force stimulates two end-organs of the inner ear, the utricle and saccule; and also produces certain changes in tension or pressure in various parts of the body which stimulate certain internal receptors called proprioceptors. In the case of an angular acceleration, another end-organ in the inner ear, the semicircular canals, is stimulated. The term vestibular sense will be used to refer both to the utricle and saccule and to the semicircular canals.

Section 3

If visibility conditions permit, and if a fixed reference, such as the horizon or a landmark, can be seen, the pilot can also detect deviations by seeing changes in the spatial relationship of the craft with the reference. In particular, the pilot uses the horizon as a reference to determine whether or not the wings are level. The greatest limitation on the use of the visual sense, of course, is the variability of visibility conditions. At night, visual cues concerning the attitude of the craft are not available or are subject to misinterpretation.

During instrument flying, the pilot's visual sense is all-important. For instance, to maintain altitude, most pilots rely on the rate-of-climb indicator, trying to keep the rate of climb averaged out at zero, and occasionally checking the altimeter.

The other activity of the pilot to be considered is control. When a pilot executes a maneuver, he controls it by applying forces to the stick (or wheel) and to the rudder pedals, and perhaps by moving the throttle. He relies on his senses (1) to control the force he applies, (2) to recognize when the airplane is satisfactorily performing the maneuver, and (3) to know when to end the maneuver. An example is his activity in making a coordinated turn. To begin the maneuver, he must move the stick sideways (or turn the wheel) and soon after apply a pedal force to counteract the adverse yaw resulting from the aileron deflection; in each case he applies what experience has taught him is the correct force for the desired turn. The

Section 3

application of these forces is controlled through the so-called proprioceptive senses, described below, which enable him to detect tension of his extremities or pressure upon them. To make the performance of the maneuver satisfactory, the pilot must prevent skidding or slipping, and control the rate of turn. Both sideslip and rate of turn produce stimuli which the pilot can sense using only the proprioceptive and vestibular senses. If the turn is coordinated, the pilot feels the resultant force acting through the seat of his pants. However, as demonstrated below, if precise control is needed and time permits, these senses must be supplemented with instruments. Similarly, to know when he has turned to the desired heading, the pilot will rely on instruments.

The importance of the feel of the controls to the pilot executing a maneuver cannot be overemphasized. In banking to turn, the pilot expects from experience a certain stick force to accompany a certain rolling velocity; he associates changes in airspeed with push or pull forces which vary in magnitude with the amount of airspeed change; in pulling out of a dive or entering a climb, he associates stick forces with the changes in normal acceleration involved; and he associates various rudder pedal forces with sideslip angles.

On the basis of interviews with pilots of jet planes, Orlansky states: "These pilots maintain their primary orientation during maneuvers (simulated combat) by reference to the horizon and stick feel.... They regard stick-feel as a particularly valuable cue because it is always available without distracting the pilot's attention from his target.... For such a man, a stick with feel is

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equivalent to a host of flight instruments" (Reference 23). The point he makes is that although a plane may be flown without feel under routine conditions by referring to instruments, when the pilot is under pressure and time is short, stick feel becomes one of the primary stimuli. The only senses for receiving these stimuli are the proprioceptive senses.

Of course in such control maneuvers as landing or take-off, the eyes are of paramount importance whether instruments are used or not.

This brief investigation shows that the senses used by the pilot can be divided into three categories: (1) visual, (2) vestibular, and (3) proprioceptive. Each of these will be treated separately.

For a summary of the material in this section up to this point, Table I, taken from McFarland (Reference 20), is presented; it lists the receptors used by each of these senses, their location, the stimuli to which they are adapted, and the function which they perform for the pilot.

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RECEPTOR	LOCATION	STIMULUS	FUNCTION
VISUAL Rods and Cones	Retina	Visible Light	1. Perception of Spatial Relationships 2. Instrument Reading
VESTIBULAR Cristae Ampullaris	Semicircular Canals (Inner Ear)	Angular Acceleration	Perception of Rotary Movement
Otoliths and Maculae	Utricle and Saccule (Inner Ear)	Gravity and Linear Accelerations	1. Perception of Changes in Position with Respect to Direction of Gravity 2. Perception of Changes in Linear Velocity
PROPRIOCEPTIVE Pacinian Corpuscles, Meissner's Corpuscles	Skin, Subcutaneous Tissue, Muscles and Tendons	Pressure or Changes in Pressure	1. Perception of Body Position or Movement and Changes in Either 2. Perception of Stick Force
Muscle Spindles, Golgi Spindles	Muscles, Tendons, Joints and Viscera	Tension or Changes in Tension	1. Perception of Body Position or Movement and Changes in Either 2. Perception of Stick Force

Table I. Receptors for the Senses Used by a Pilot in Stabilizing and Controlling an Airplane Together with Stimuli to Which They Are Adapted (Reference 20)

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(a) THE VISUAL SENSE

The receptors for the visual sense are, of course, the eyes; the end-organs are the rods and cones, which are located inside the retina and are so-called because of their appearance. The retina, which is the innermost layer of the eyeball, is less than .5 mm thick at the thickest point.

The associated neurones found in the retina behind the rods and cones are of two types: some, called bipolar neurones, have their end-brushes in synapses with the dendrites of fibers of the optic nerve, which is the main channel to the brain for impulses produced by the effect of light on the rods and cones; others, called lateral neurones, connect either different fibers of the optic nerve, or a bipolar neurone to several rods or cones. An impulse produced in a bipolar neurone is transmitted by that neurone to a fiber of the optic nerve and from there to the optic center of the brain; and, due to the interconnection provided by the lateral neurones, this impulse can be transmitted to several different fibers of the optic nerve.

At the center of the retina is a small pit, called the fovea. It is surrounded by a small yellow ring, the macula. Slightly to the nasal side of the fovea, the optic nerve enters, and its fibers branch out to all parts of the retina. At the point of entry, the fibers of the optic nerve form a bundle approximately 2 mm in diameter resulting in a blind spot at that point. In the fovea, there are no rods, only cones, but in the macula, there are rods as well as cones. The proportion of rods to cones increases with distance

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from the fovea. In the rest of the retina, called the periphery, the rods predominate, the cones decreasing in number as the edge of the periphery is approached until their numbers are negligible.

Psychologists and physiologists are agreed that the rods are the end-organs for brightness vision and the cones for color and form. The cones function best under conditions of bright (or photopic) illumination, as in daylight, and are very insensitive in darkness (scotopic illumination). On the other hand, the rods are much more sensitive to light and function best in relative darkness.

The assumption is made that the nervous impulse is excited by a photochemical reaction in the rods and cones; that is, one or more chemical reactions occur in a rod or cone when it is exposed to light, and as a product of these reactions, a substance is formed which stimulates the neurones and produces the impulse. There is evidence in support of this theory for the rods but not for the cones. The rods contain a purple substance, visual purple or rhodopsin, which is known to be photosensitive: it is quickly turned white by light. When the light is removed, the rhodopsin slowly resumes its purple color.

This photochemical change in rhodopsin offers an explanation of the phenomena of dark adaptation and light adaptation. If a person remains in a brightly lighted room, the rods are rendered insensitive by the action of light on rhodopsin. When he then passes into a dark room, vision is very poor due to this insensitivity; but gradually, as the rhodopsin is restored, the rods regain their normal sensitivity

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to dim light, and vision improves. This process, which may require up to half an hour, is called dark-adaptation. Conversely, if the person remains in a dark room long enough that the rods are at normal sensitivity, entrance into a room with normal illumination gives a sensation of glaring brightness. However, vision quickly returns to normal as the rhodopsin is rapidly altered by the light. This process is called light-adaptation.

Reference 10 mentions a very important practical application of these principles. It is known that of all wave lengths of light, those corresponding to red have the least effect on the rhodopsin of the rods. An obvious method of shortening the long time required for dark adaptation of sailors preparing to go on watch at night was to have the men wear red goggles from the time they awakened until they were on the deck in the dark, thus preserving the dark adaptation acquired during sleep. Similarly, the advantage of using red lights for airplane instrument panels to minimize shifts in adaptation level for night flying is clear.*

Another application of these principles takes advantage of the fact that the peripheral region of the retina is more sensitive to dim lights than the other areas due to the preponderance of rods there. Therefore, men on night watches during the war were trained to search for lights on the horizon by scanning above or below the horizon (Reference 10).

*For detailed discussion of the application of these considerations to the problem of cockpit illumination, see MacFarland, Reference 20.

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In addition to the light-sensitive rods and cones, the eye includes both a lens for focussing the image on the retina and a pupil which varies the aperture of the lens by a reflex movement as the light intensity varies. The focal length of the lens is also varied automatically as the distance from the eye to the perceived object changes; this is a function of the ciliary muscles which change the curvature of the lens; for near objects, the curvature is increased to shorten the focal length whereas for distant objects the curvature is decreased to increase the focal length. This process is called accommodation. As the eyes are shifted from a distant object to one nearby, not only must the focal length of the lenses be changed, but also the eyes must be rotated in synchronization to converge on the object so that the image falls on corresponding parts of the retina of either eye. If convergence is not properly accomplished, the image will fall on different portions of the retinas causing perception of a double rather than a single image. There is a minimum object distance for which convergence is possible; this minimum increases with age.

In landing or take-off, a pilot is called upon to focus alternately on such a nearby object as an instrument and then on a more distant one, such as the edge of the runway. If, under these conditions, he is called upon to make a response, his reaction time will be increased by the time required for the accommodation and convergence, as he changes focus, over and above his simple reaction time when he fixes his eyes successively on the same object. The Tufts College Handbook (Reference 10) quotes the results of an experiment conducted by Travis to measure

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this variation of simple reaction time. In this experiment, fifty subjects were required to identify a certain feature of objects at distances of 22 inches and 43 feet as quickly as possible, the objects in both cases subtending the same visual angle (see below). To do this, the subjects fixated successively on only the near object or on only the far object, or alternately on the near and far objects, with one or both eyes. The feature to be identified had four possible values. The results are given in Table II.

FIXATION CONDITIONS	MEAN REACTION TIME PER FIXATION (SECS)	RANGE (SECS)
1. Binocular: Alternate	1.065	.72 - 1.89
2. Left Eye: Alternate	1.235	.70 - 2.30
3. Right Eye: Alternate	1.195	.70 - 2.90
4. Binocular: All Near	.900	.50 - 1.45
5. Binocular: All Far	.840	.50 - 1.78

Table II. Results of an Experiment To Find
the Time Required for Accommodation
and Convergence (Reference 10,
Part VI, Chapter II, Section I, p. 10)

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The significance of the results is that the average time difference between the reaction time after successively refixating near and far objects and that after refixating near only or far only is .2 seconds. Averaging the mean reaction time for Conditions 1, 2, and 3 of Table II gives 1.165 seconds, which is approximately .3 seconds more than the average of Conditions 4 and 5, indicating that the time required to refixate near and far objects is .3 seconds more than the time required to refixate objects at the same distance.

The properties of vision which will be examined here are: (1) acuity, (2) depth perception, and (3) perception of movement. (Color vision is not considered to be within the scope of this volume.)

Since the experiments reported in the following pages can be described most efficiently in the jargon of psychology, some terms will now be defined according to their usage in Reference 10.

When an eye is fixed on a certain object, the entire area visible is called the visual field area. The angle subtended at the eye by the field or by a certain portion of it, is referred to as the visual angle of the field or of the portion thereof.

The dimensions of the monocular visual field are specified in terms of visual angles. On the horizontal plane, this angle is from 140° to 160° , i.e., from 60° to 70° on the nasal side of the fixated object and from 80° to 90° on the temporal

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side. Vertically, the visual angle is 130° , i.e., 50° up and 80° down. Naturally there is a region, common to the visual fields of either eye, which is seen by both eyes if they are fixated on an object; this region is called the binocular field of vision. Figure 1, taken from Reference 10, shows the projection of the visual field on a plane perpendicular to the line of sight.

The visual field can also be divided into the fields of foveal vision and peripheral vision. The field of foveal vision is that area surrounding the object being fixated which subtends a visual angle of approximately 3° . The rest of the visual field is the field of peripheral vision.

1. ACUITY

This term refers to the ability of the eyes to perceive form. It is usually measured in terms of the visual angle subtended by a just recognizable stimulus. There are three aspects of acuity which are measured. The first is the ability to perceive whether an object is present or not; it is measured by the smallest angle which an object can subtend and still be visible. This angle is called the minimum perceptual acuity. The second is the ability to detect when two objects are separated, measured by the smallest visual angle which can be subtended by the gap between the objects for them still to be recognized as separate. This angle is the minimum separable acuity. The third aspect of acuity, reported by Bates in Reference 2, concerns the minimum percent of difference between two qualities of an object for its form to be distinguished.

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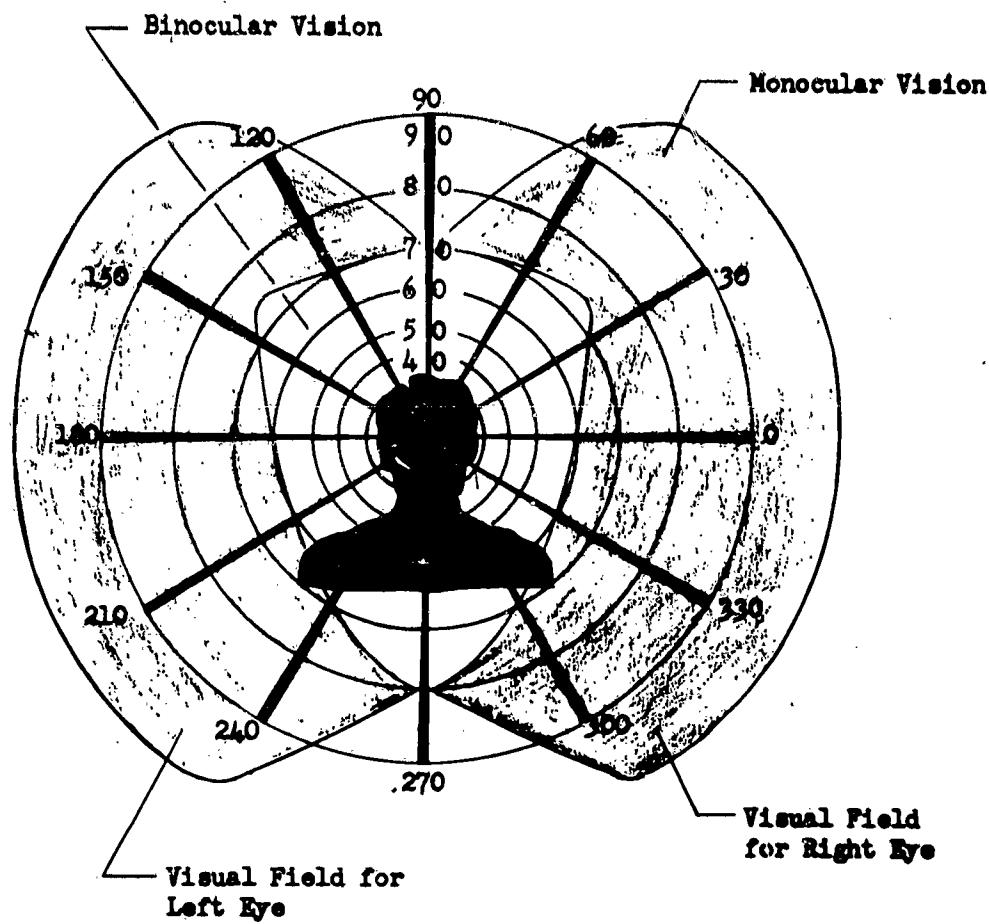


Figure 1. Projection of the Visual Field on a Plane Perpendicular to Line of Sight. Shaded Areas Are Fields for One Eye Alone; White Area Is Binocular Field (Reference 10, Part III, Chapter I, Section I, p. 4)

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Specifically, Bates considers a cross formed by two lines. If the crossbar intersects the longitudinal axis of the cross at a point other than the center, segments of unequal length will be intercepted on the longitudinal axis. The problem investigated was to determine what percent difference must exist between these segments for a subject to perceive correctly that the crossbar does not intercept the midpoint of the longitudinal axis. The results are shown graphically in Figures 2 and 3. Figure 2 plots the minimum difference in length (as a percent of original length) which would allow 90% of the subjects tested to detect that the crossbar was off-center as a function of the average visual angle subtended by the two segments. Note that if the visual angle is greater than 30 minutes, the minimum perceptible difference is constant at 5%, but as the angle decreases below 30 minutes, the minimum difference increases rapidly. This has an obvious significance for the magnification of visual presentations: magnifying the object until it subtends an angle of 30 minutes is an important aid to accurate perception, but beyond this size, magnification has no marked effect in improving acuity.

Figure 3 plots the probability of correct perception that the crossbar is off-center as a function of the length of time that the stimulus is presented to the subject. A family of curves is obtained with the percent-difference in lengths of the intercepted segments as the parameter.

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The Threshold for Perceiving
That the Cross-Bar Is Off-Center
Expressed in Terms of
Percentage Difference Between
Lengths of Intercepted Segments

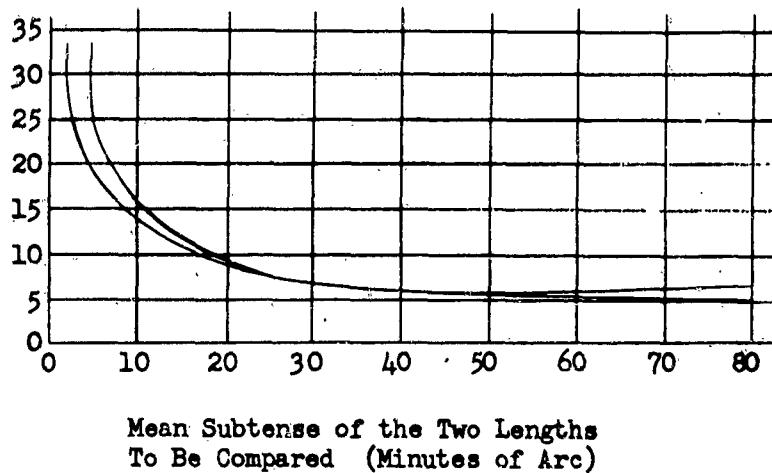


Figure 2. Visual Acuity as Measured in the Cross-Bar Experiment Described in the Text. The Ordinate Is the Least Percentage Difference Between the Intercepted Segments Which Would Enable 90% of the Subjects to Perceive That the Cross-Bar Was Off-Center. (The Two Curves Represent an Envelope for Different Experiments.) (Reference 2)

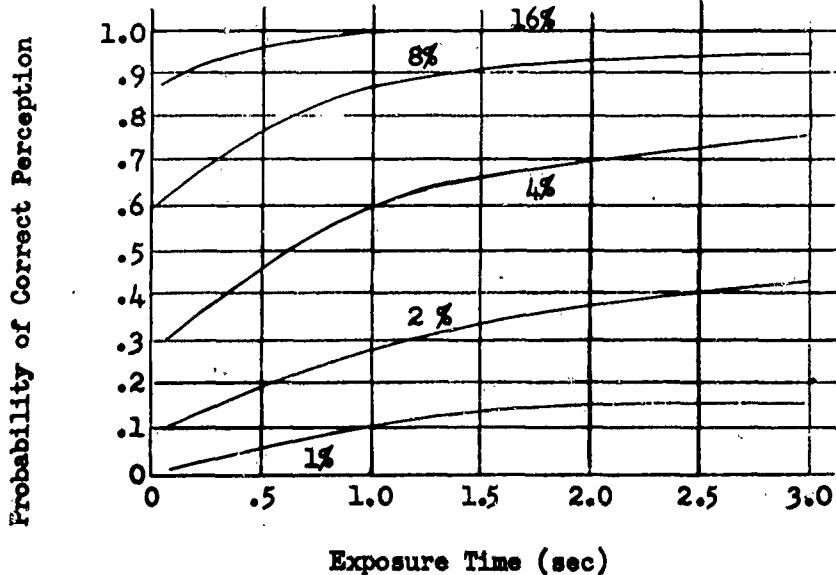


Figure 3. The Variation of Visual Acuity with Duration of Stimulus as Measured by the Probability of Correctly Perceiving That a Cross-Bar Was Off-Center, for Various Percentage Differences in Lengths (Reference 2)

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Although caution must be observed in generalizing from such a particular experiment, the inference can be drawn that 2 seconds is required for maximum acuity to develop and that longer exposure does not improve acuity.

Figure 2 is interesting in connection with Weber's Law. According to this famous law, the ratio of the minimum change in stimulus intensity which can be perceived to the intensity of the original stimulus is a constant:

$$\frac{\Delta I}{I} = k$$

where I is the intensity of a stimulus

ΔI is the least change in this intensity which can be perceived as change

k is a constant for a given sense modality

This law is found to be valid only for a limited range of stimulus intensities; it is unreliable at very low or extremely high intensities. Nonetheless, it is a useful and practical generalization which can be applied in many situations. If the original stimulus intensity in the crossbar experiment is taken to be the length of a segment when the crossbar is in the middle, and if the ΔI is chosen as the least difference in length which will cause the subject to perceive the difference in position of the crossbar, then the ordinate in Figure 2 is simply the ratio $\Delta I/I$ (multiplied by 100 to express it as a percent). According to Weber's Law, this ratio should be constant and the graph a horizontal line. And indeed it is, for the range

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of stimulus intensities (lengths) such that the average visual angle subtended by the segments is greater than 30 minutes. Below this level of intensity, the value of $\Delta I / I$ increases rapidly, indicating that a proportionally greater change is required to be perceptible than when the intensities are larger. The value of the ratio is seen to be approximately .05 for the visual sense in this particular experiment.

Table III is taken from Reference 10 where various experiments are reported to establish minimum perceptual and separable acuities.

TYPE OF ACUITY	CONDITIONS	VALUE
Minimum Perceptible	Luminous Point, e.g., a Star	No Lower Limit; for the Star Mira, a Spot of .056 Sec Was Perceived
	Dark Square Against a Bright Sky	14.2 Sec
	Thin Wire Against a Bright Sky	1 Sec
	The Same (Different Experiment)	.43 Sec
Minimum Separable	Luminous Points on a Black Background	180 - 200 Sec
	Lines on a Grating	64 Sec

Table III. Threshold for Two Types of Acuity in Terms
of Visual Angle Required for Perception
(Reference 10, Part III, Chapter II,
Section III, p. 1)

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An important aspect of acuity for aviation is the nature of its variation with increasing distance. The Tufts College Handbook reports an experiment showing that visual acuity improves as the distance of object to be perceived is increased from .2 meter to 1 meter. On the other hand, three separate experiments indicate that for larger distances, acuity is independent of distance. Specifically, for ranges of from 5.94 to 113.2 feet, from 8 to 23 meters, and from 12.5 feet to 2,83 miles, the three experiments showed that acuity did not vary appreciably. It is important to remember that acuity is measured in terms of visual angle subtended at the eye.

Investigation of acuity at low levels of illumination are also significant. Since there are no rods in the fovea, and since the sensitivity of the rods to dim light is much greater than that of the cones, it seems clear that maximum acuity under scotopic illumination will be obtained at some angle from the center of the eye. The same source, Reference 10, reports experiments confirming this. Under scotopic illumination, maximum acuity is developed if the object to be perceived is presented at an angle of from 4° to 8° from the center of the eye toward the temporal side. At the very lowest levels of scotopic illumination, there is no angle of presentation which makes acuity maximum; acuity remains constant as the angle varies from 4° to 30° .

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2. DEPTH PERCEPTION

Numerous factors combine to give the pilot perceptions of spatial relationships, all of them conditioned by learning and experience. The significance of learning is overlooked in ordinary observation because spatial relationships are perceived without awareness of what cues are being used and so quickly that the process seems immediate. This process of learning and experience affects space perception so greatly in a practical situation that it is very difficult to generalize from laboratory experiments to field conditions.

Monocular depth perception amounts to perceiving differences in the distances of objects viewed. The factors which enable a subject to perceive distance relationships with one eye include the following:

1. Size of Retinal Image. An observer judges the distance to a familiar object according to the size of the retinal image. The image size is compared with what the subject knows is the actual size of the familiar object and the discrepancy is interpreted in terms of previous experiences of viewing. This cue obviously requires learning and experience, for if the object is unfamiliar, little information is furnished by image size.

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2. Brightness. In the laboratory, it is found that increasing the light intensity on disks causes them to appear nearer.
3. Proprioceptive Cues due to Accommodation. The action of the ciliary muscles in altering lens curvature to focus the image (see discussion above) produces proprioceptive stimuli which give cues about the relative distances from the subject of different objects as the subject shifts focus from one to the other. It is stated in Reference 10 that although these cues are used, they play a minor role, and that they become ineffective at a distance of two yards. They therefore have little significance for the pilot.
4. Interposition. When one object obscures part of another, the first is interpreted to be the nearer.
5. Shadows. Similarly, if one object casts a shadow on another, their relative distances are interpreted according to the direction of the light which illuminates them.
6. Highlights. Convex surfaces show highlights, whereas concave surfaces show shadows.
7. Aerial Perspective. The outlines of distant objects are more blurred than those of nearer objects.

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8. Angular Perspective. The observer expects the planar projection on his retina of the portion of space he is viewing to show parallel lines converging with distances. Therefore, if parallel references are available, he will judge distance partly in terms of the extent of this convergence.

9. Relative Movement. If the observer is moving and he fixates on some object, more distant points appear to move with him whereas nearer objects appear to move in the opposite direction.

10. Relation of Object to Observer and Skyline. Using these two fixed points as references, the observer judges distance relationships by locating the objects along a linear scale whose endpoints are the horizon and his position.

For binocular depth perception, extra cues are available which make binocular depth perception more accurate than monocular at close range. These are:

1. Retinal Disparity. When both eyes converge on one object, each receives a slightly different view. This discrepancy is resolved neurologically, by an unknown process, into a single visual impression characterized by depth. Retinal disparity is probably the major factor in binocular depth perception at close range. However, it is stated in Reference 10 that the two retinal images are practically identical at distances over 200 yards. Therefore this cue disappears when distances are large.

2. Different Parallactic Angles. The parallax angle is defined as the angle formed by the two lines joining one point on an object to the two eyes. Parallax angle decreases as distance increases, and the observer makes use of variations in parallactic angles to judge variations of distance. A measure of the threshold of depth perception is the difference in parallactic angles of two objects when one first becomes noticeably nearer. Reference 10 quotes an experiment indicating that 2 seconds of arc is the lowest threshold, but that 12 seconds of arc is the accepted value in practice.

3. Proprioceptive Sensations of Convergence. The inward rotation of the eyeballs as focus is shifted from distant to nearby objects also produces sensations which experience has taught the observer to interpret in terms of distance relationships. According to Reference 10, this cue, like retinal disparity, becomes ineffective for distances over 20 yards. When retinal disparity is not effective, the factors of relative size, interposition, and relative movement, which are all monocular cues, become primary; therefore, it should be expected that the superiority of binocular depth perceptions over monocular is not so pronounced at distances exceeding twenty yards. Experiments verify this: Hirsch, Horowitz, and Weymouth, according to the Tufts College Handbook, found that the superiority of binocular to monocular depth perception is most pronounced at distances of approximately 18 yards,

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and that the two are equally effective at a distance of 3600 feet. Since most of an aviator's distance judgments are made at ranges where retinal disparity has become ineffective as a cue, these findings are significant. Reference 10 also mentions experiments in which pilots made successful landings with the binocular field eliminated by special goggles and other experiments in which the monocular field was eliminated. Absence of the peripheral field produced errors no more serious than did elimination of the binocular field. It seems that to compensate for loss of binocular vision, pilots made greater use of the monocular cue of relative motion. When an object is set in motion, binocular depth perception deteriorates, but monocular perception improves, again demonstrating that binocular vision is not always superior to monocular in a situation which is very common in aviation.

Errors in depth perception are increased up to 70% as illumination of the object viewed is decreased. In particular, judgments about the distance of an isolated object are extremely unreliable at night, especially when other references are lacking.

3. VISUAL PERCEPTION OF MOTION

Real continuous movement of a single object results in the successive stimulation of a certain sequence of receptors in the retina. The resulting discrete stimuli are integrated somehow in the central nervous system so that

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what is perceived is a continuous altering of the spatial position of that object. There is both an upper and a lower limit to the rates of movement which can be perceived. For rates which are too slow, all that is seen is a single object occupying a series of different positions; for rates which are too high, nothing at all is perceived.

Apparent movement is perceived when two or more similar stimuli are presented in fairly rapid succession to different receptors. Here, too, the integrating action of the central nervous system causes the perception of a single object in continuous motion; and again the rates of succession allowing this perception have upper and lower limits.

Apparent movement of this type is referred to as the Phi-phenomenon. Figure 4 illustrates this phenomenon. In (a), if lines 1 and 2 are presented in that order a short time apart, continuous clockwise movement is sensed; but in (b), where the figure is the same but the order of presentation is reversed, it appears that line 1 is rotating continuously in a counterclockwise direction. In each case, the lines appear to move through the shortest distance between the two positions. But in (c), when the four figures are presented in rapid succession, the intervening positions, 2 and 3, cause perception of clockwise rotation of the lines even though the shortest distance would be in a counterclockwise direction.

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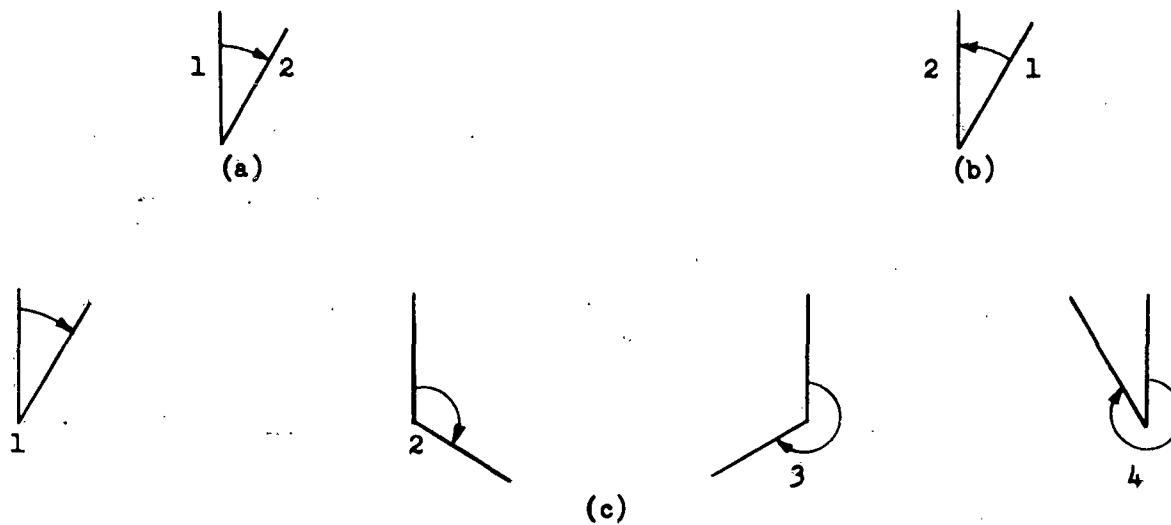


Figure 4. Illustration of the Phi-Phenomenon

Two measurements can be made concerning the perception of movement. One of these is the measurement of the rate of movement which is just perceptible; as mentioned above, this gives both upper and lower values. This measurement can be expressed in terms of visual angle traversed per unit of time. The values obtained are the absolute thresholds (upper and lower). The other measurement is of the minimum difference in the velocities of two objects which allows correct perception of the fact that the rates of movement are different: this difference is called the relative threshold.

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Reference 10 contains a summary of the thresholds which have been established. The experiments are all extremely specific, and generalization is difficult. Some of these values were converted from linear to angular velocities, in terms of visual angle, to obtain numerical values not explicitly dependent upon the subject distance from the stimulus. Table IV, taken from Reference 10, summarizes these results.

It might be expected that real motion could be perceived as soon as an object viewed had traversed a certain fixed visual angle and that there should therefore be no lower limit to rates of movement which would cause perception of motion, provided that the subject was exposed to the stimulus long enough. This hypothesis would suggest that the product of absolute threshold multiplied by time of exposure would be a constant. Tests were conducted during which absolute thresholds for movements were measured as the time the subjects were exposed to the stimulus was varied; the results given in Condition 2 of Table IV show that this supposition is not valid.

Note that the values for Conditions 1 and 2 in Table IV are for daylight conditions: evidently Condition 4 also involved photopic illumination because foveal vision was used. The threshold for Condition 3 is for scotopic illumination, and therefore peripheral vision was used to take advantage of the higher sensitivity of the rods under that condition.

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CONDITIONS OF EXPERIMENT	EXPOSURE TIME	LOWER THRESHOLD	ABSOLUTE THRESHOLD
1. Black Square Moving Rectilinearly on a White Background. Daylight Illumination. Subject Was 2 Meters from Stimulus. Monocular Foveal Vision.		Lower Threshold: 6 min 35 sec/sec Upper Threshold: 35 deg 29 min 20 sec/sec (Reference 10 Gives: .383 cm/sec and 142.5 cm/sec)	
2. White Square Moving Rectilinearly on a Dark Background. Daylight Illumination. Subject Was 240 cm from Stimulus. Monocular Foveal Vision. Exposure Time Varied from .5 sec to .4 sec.	.5 sec *1.0 sec *2.0 sec 4.0 sec	2 min 34 sec/sec 1 min 12 sec/sec 54 sec/sec 44 sec/sec	
3. Gaps in a Black Ring which Was Rotating against a White Background. Scotopic Illumination. Subject Was 48 cm from Stimulus. Monocular Peripheral Vision. Exposure Time Was 2 - 3 sec.			LOWER THRESHOLD
4. Black Squares Moving Vertically at Different Rates against a White Background. Subject Was 2 Meters from Stimulus. Monocular Foveal Vision.		1. For Inner Periphery: 4.34 deg/sec 2. For Outer Periphery: 8.09 deg/sec	1. For Inner Periphery: 4.34 deg/sec 2. For Outer Periphery: 8.09 deg/sec
5. Black Gratings Moving Horizontally on an Illuminated Background. Subject Was Dark Adapted. Monocular Vision; Edge of Fovea. Exposure Time Was .2 sec.			RELATIVE THRESHOLD 4 min/sec Is Minimum Perceptible Difference when Constant Speed of Other Square is 2 deg 52 min/sec. (Reference 10 Gives .24 cm/sec and 10 cm/sec)
			THRESHOLD FOR DETERMINING DIRECTION OF MOVEMENT
			12 min 19 sec/sec

Table IV. Thresholds for Perception of Movement in Terms of Visual Angle Traversed per Second (Reference 10, Part III, Chapter II, Section VII, p. 4. Asterisked Values from Reference 6 Included by Author of This Volume)

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Another experiment, reported in Reference 10, measured the absolute thresholds for perception of motion; twenty-eight subjects with 20/20 vision were examined; the tests were conducted under scotopic illumination and at various retinal positions. The subjects were all dark-adapted, and monocular vision was used. These results are recorded in Table V.

RETINAL POSITION (Deg from Fovea)	MEAN THRESHOLD (Deg of Visual Angle per Sec)	STANDARD DEVIATION
7°	.348	.196
10°	.340	.191
25°	.431	.239
35°	.518	.285
45°	.647	.350
55°	.823	.453

Table V. Thresholds for Perception of Movement under Scotopic Illumination at Different Retinal Positions (Reference 10, Part III, Chapter II, Section VII, p. 7)

The wide variability from subject to subject in this test was noteworthy, especially since they all had normal visual acuity. For the subject making the poorest showing, the thresholds were 40 times as great as those for the best.

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Perceptions of movement may also be illusory; these illusions are not to be confused with the apparent motion produced by the Phi-phenomenon; they occur when the stimulus-object is actually at rest, but faulty interpretation of sensory data ascribes motion to it.

MacFarland, in Reference 20, describes the oculogyral illusion and its effects. This illusion, which results when the pilot is subjected to rotary motions, is caused by a reflex response consisting of movements of the eyeball produced when the semicircular canals are stimulated by angular acceleration. The illusion is that after the pilot has stopped rotating, objects in his field of vision appear to be revolving about him in the opposite direction. Under scotopic illumination, this illusion can be caused by angular accelerations on the order of $.3 \text{ deg/sec}^2$; when the illumination is photopic, the angular accelerations must be much larger to produce this illusion. As MacFarland says, ordinary rotational accelerations experienced in flight can be expected to produce this illusion at night. The inherent danger can be illustrated by the following example: After recovering from a spin to the left which involves large accelerations, a pilot will sense a turning to the right, and if he attempts to correct for this illusory turning, he will cause the airplane to spin to the left again. This could result in a neutral stability. Unfortunately, this reflex response of the eyeballs cannot be eliminated, and the only remedy is to train the pilot to ignore the sensation it produces.

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The so-called auto-kinetic illusion is the apparent motion of a stationary object. Unlike the oculogyral illusion, no movement of the eyeballs is involved. It occurs mainly when fixed visual references are unavailable, as in night formation flying; it seems to follow fixation of the object after approximately 9 seconds and may last as long as 10 seconds. Both the apparent rates and the apparent displacements are small: from $.2^{\circ}$ /sec to $.3^{\circ}$ /sec and from 3° to 4° respectively, in terms of visual angle. According to the Tufts College Handbook (Reference 10), it is universally experienced by normal pilots.

Other illusions referred to in Reference 10 are (1) the after-image illusion, (2) the cloud-moon illusion, and (3) the size-distortion of a moving object. The after-image illusion follows the passage of a light stimulus over the retina in a given direction for a certain length of time (not well-defined) producing a sensation of motion at the same speed but in the opposite direction immediately after the original stimulus ceases; the sensation lasts approximately 6 seconds. As its name suggests, the cloud-moon illusion is the incorrect perception of which of two objects is stationary and which is moving; the smaller, dimmer object tends to be considered moving. The size-distortion illusion is the apparent shrinking in size of a fast-moving object; the shrinkage varies directly with speed.

All these illusions are universally experienced, and their effect in lowering accuracy of the pilot as a sensor must be taken into account.

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In concluding this discussion of the visual sense, it should be pointed out that the Tufts College Handbook is an invaluable source of information concerning not only the measurement and testing of visual data, but the application of these data to Human Engineering; it also contains extensive bibliographies. Particular attention should be directed to the section on legibility of instruments. The extent to which this source was relied upon to provide the data considered pertinent here should be obvious from the numerous references made to it.

(b) THE VESTIBULAR SENSE

The pilot perceives changes in linear or angular velocity or changes in position primarily through the vestibular senses, even though these perceptions may be indirectly reinforced by the visual sense and by pressure or tension cues from the proprioceptive senses. Figure 5 shows the end-organs for these senses; they are parts of the inner ear on either side of the head. The term "vestibular sense" really includes two separate senses. The end-organ for one of these consists of the semicircular canals (including the ampullae); the specific stimuli to which this end-organ is adapted are changes in angular rotation in any one of these mutually perpendicular planes (see discussion below). The end-organ for the other part of the vestibular sense consists of the utricle and saccule, specifically adapted most probably to changes in the resultant force acting on the head and therefore to changes in linear velocity as well as to changes from one static position to another with respect to the direction of gravity. The following discussion of the vestibular sense deals separately with these two senses.

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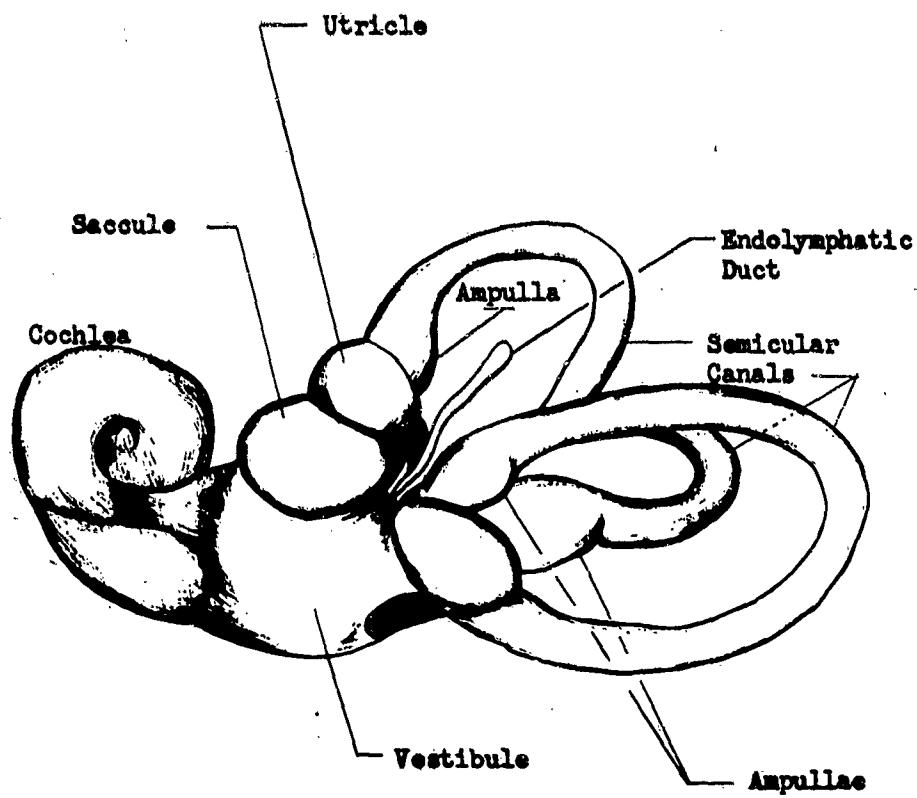


Figure 5. The Vestibular Organs of the Inner Ear

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1. THE SEMICIRCULAR CANALS

There are three semicircular canals, all opening into a common vestibule. One canal lies in a horizontal plane and curves toward the back of the head; the other two lie in vertical planes, one curving toward the back of the head, the other toward the top of the head. At the base of each canal is an enlargement called the ampulla; these ampullas contain cells with hairy endings, the cristae ampullaris, attached to the membrane. Each canal and ampulla is filled with fluid, the endolymph. The cristae ampullaris are the receptors for the semicircular canal end-organ. Mechanical stimulation of the hairlike endings initiates a nervous impulse. To be precise: when an individual begins to be rotated in the plane of a canal, or indeed whenever his rate of rotation in that plane is changed, the inertia of the endolymph causes it to flow backward relative to the direction in which the canal is moving. The cristae ampullaris, being attached to the ampulla at one end, move with it and the backflow of fluid exerts a pressure on the hairlike endings of the cristae. This is the mechanical stimulation which produces the nervous impulse.

If the rotation is continued at a uniform rate, the endolymph quickly begins to move with the canal and no pressure is then exerted on the ends of the cristae. Consequently, no rotation is felt. When the rotation of the head is stopped, the inertia of the endolymph causes it to continue rotating in the canal which is now stationary. Again a pressure is exerted on the hairs of the cristae but in a direction which gives the sensation of rotation in the opposite direction.

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although the head is stationary (this is the stimulus producing the nystagmus reflex which is responsible for the oculogyral illusion mentioned above). The explanation offered here that the source of sensations of angular acceleration is endolymph flow is not accepted by all physiologists, some maintaining that the capillary size of the canals and relatively high viscosity of the endolymph argue against such a continuous flow as described above. It is true that the description may be oversimplified when viewed as a fluid-flow phenomenon; however, experiments have proved that the endolymph is displaced, whether continuously or not, when the canals are rotated. With these reservations, the endolymph flow theory can be offered as a suggestive and useful working model for semicircular canal action.

Impulses from the semicircular canals produce many reflex responses: nystagmus has already been mentioned; in addition, reflex contractions of stomach muscles, vomiting (for heavy stimulation), increased sweating, and compensatory adjustments of head, torso, and limbs to maintain posture are reflex reactions to vestibular stimulation. Each of these reactions produces accompanying sensations. Actually, it is not known if vestibular sensations are directly represented in consciousness; it may well be that a pilot's only conscious perception of acceleration is indirect and due to the perception of the reflex responses produced by the stimulation of the semicircular canals, rather than to the perception of the impulses from the canals.

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Since it is not definitely known how these impulses are produced or whether they are perceived directly or indirectly in the consciousness, and since it is very difficult to examine the organs, experiments on the perception of angular acceleration are not very definitive, and the values obtained show great variation. Yet the need for obtaining threshold values for the perception of angular acceleration is widely felt, and more and more effort is being directed along these lines. Table VI gives values which MacFarland, in Reference 20, obtained from American, German, and Russian sources.

DURATION OF ANGULAR ACCELERATION (SEC)	THRESHOLD (DEG/SEC ²)
2	4.5
8	2.0
9.5	1.14
14 - 16	2 - 3
20	1.3

Table VI. Minimum Angular Accelerations which Can Be Perceived as Functions of the Duration of the Stimulus (Reference 20, p. 360)

The same source suggests that a threshold value of angular acceleration of from 1 to 2 deg/sec² be assumed for the accelerations likely to be encountered in flight.

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2. THE UTRICLE AND SACCULE

The utricle and saccule (see Figure 5) are small sacs, each containing fluid and a membrane (the macula) to which small hair cells are attached. On these hair cells rest numerous crystals (calcium carbonate) called otoliths. In the utricle, the macula is horizontal; in the saccule, it is vertical. The hair cells of the macula are the receptors for these end-organs, but the maculae and otoliths are sometimes considered to be the receptors. It is believed that the specific stimulus for these receptors is a change in the resultant force on the head, whether due to a linear acceleration in the horizontal or vertical plane, or to a change from one static position to another with respect to the direction of gravity. According to this view, changes in the direction or magnitude of this resultant force cause a displacement of the otolith crystals and therefore a bending of the hair cells on which they rest. It is this bending which produces the nervous impulse in the associated nerve endings.

For example, if the only movement which a pilot undergoes is tilting, the direction of gravity relative to the maculae will be changed, the otoliths will be moved, and the pilot will sense a change in position. Now, suppose that instead of being simply tilted, the pilot is making a banked turn. In this case the otoliths will be moved by a force which is the resultant of the force due to acceleration and the force due to gravity. The pilot either will not sense the tilt at all or else will sense it

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incorrectly, unless a visual reference is available. One of the functions of the visual sense is, then, to correct erroneous information supplied by the otolith organs concerning the pilot's position in space. This method is satisfactory in contact flying, but it means that instruments must be relied upon when visibility is impaired. In any case, the pilot must learn to interpret these visual cues.

Graybiel is quoted by MacFarland in Reference 20 as saying: "If in the absence of visual orientation, man is subjected to accelerative force, the perception of the vertical will eventually coincide with the direction of the resultant of this force and the force of gravity." The corollaries of this statement, also given by MacFarland are:

- I. If visual cues provide no clues about orientation with respect to the earth:
 - a. "If the body maintains a constant relationship with the direction of the resultant force (by tilting with the airplane), one will not be aware of any change from the true vertical position.
 - b. "If the body maintains a constant relationship with the true vertical, one will be conscious of a tilt or rotation. The apparent change from the true vertical position will be equal, eventually, to the angular displacement which the resultant force makes with the true vertical and will be in the same plane. Both the direction and degree of apparent displacement will be independent of a particular position of the body.

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II. "If objects in the field of vision do provide clues for orientation to the earth, a conflict between visual and otolithic stimuli... [is resolved in favor of] visual orientation to the earth."

The statements made above concerning whether impulses produced by the semicircular canals are directly and consciously perceived, or whether they are only indirectly sensed by perception of the reflex reactions made in response to them, apply here.

Thresholds for the otolith organs involve thresholds for perception of linear acceleration and for perception of tilt, the latter under both static and dynamic conditions.

Two sources, one a paper by Ruff and Strughold, the other a paper by Armstrong, are reported by MacFarland as listing the following values for thresholds for perception of linear acceleration; these are given in Table VII (with equivalent values in terms of g units):

PLANE OF ACCELERATION	SOURCE	THRESHOLD	
		CM/SEC ²	g
Horizontal	Ruff Armstrong	10	.01
		2 - 20	.002 - .02
Vertical	Ruff Armstrong	12 4 - 12	.012 .004 - .012

Table VII. Minimum Perceptible Linear Accelerations
(Reference 20, p. 360)

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Armstrong's data were obtained from a survey of the literature and are just as variable as were data on thresholds for angular acceleration. Again threshold values decrease as time of exposure is increased.

Static perception of tilt is fairly sensitive, although exceedingly variable, as shown by the ranges and standard deviations in the experimental results given in Table VIII. These data were obtained by tilting blindfolded subjects in a tilt chair, and are presented by MacFarland.

DIRECTION OF TILT FROM VERTICAL	216 STUDENT PILOTS	599 CADETS	95 INSTRUCTORS
Right			
Mean Threshold, Deg	2.34	2.39	1.94
Standard Deviation, Deg	1.06	1.55	1.38
Range, Deg	.4 - 6.9	.4 - 14.0	.7 - 7.4
Left			
Mean Threshold, Deg	2.14	2.29	1.93
Standard Deviation, Deg	.93	1.39	1.25
Range, Deg	.5 - 4.8	.1 - 10.3	.4 - 10.3
Forward			
Mean Threshold, Deg	2.12	2.69	2.77
Standard Deviation, Deg	1.32	1.67	1.82
Range, Deg	.2 - 7.2	.2 - 12.2	.6 - 10.2
Backward			
Mean Threshold, Deg	2.99	3.25	3.25
Standard Deviation, Deg	1.99	2.24	2.28
Range, Deg	.2 - 9.7	.1 - 14.3	.5 - 13.9

Table VIII. Minimum Tilt Angles which Can Be Perceived under Static Conditions by Blindfolded Subjects (Reference 20, p. 361)

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No information was presented concerning the time required to sense the tilt. However, data from the Tufts College Handbook indicate that perception of tilt is much less sensitive under flight conditions than at rest and is relatively slow. In this experiment, three trained subjects were blindfolded and seated in an airplane which was put through a series of maneuvers. The subjects were required to report the direction and duration of tilting and turning and to estimate the accelerative forces experienced. The airplane was tilted at six bank angles (10° , 18° , 30° , 40° , 50° , and 60°), and each subject made twelve observations at each angle.

The results, taken from Reference 10, were:

1. Time from onset of turn to perception of turn: 9.8 seconds (average)
2. Time from onset of bank to perception of bank: 7.5 seconds (average; independent of bank angle)
3. Duration of bank was grossly underestimated: for a turn lasting 160.3 seconds, the average estimate of duration was 20.9 seconds
4. 75% threshold for bank: 18° (75% threshold is defined to be the minimum bank angle which was perceived in 75% of the trials)
5. Tilt angles were always underestimated
6. Estimates of accelerative forces were accurate

Result 5 is in accord with the corollary to Graybiel's statement quoted above. The subject's perception of the vertical was impaired because he was subjected to the additional accelerative force caused by the turn: the larger this force, the greater the impairment. Table IX gives the average amount of tilt estimated by the subjects for each bank angle.

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ANGLE OF BANK (DEG)	MEAN REPORTED TILT (DEG)
10	4.1
18	5.1
30	7.2
40	8.1
50	10.6
60	11.9

Table IX. Estimates of Tilt Angles Made by Trained Blindfolded Subjects in Actual Flight (Reference 10, Part V, Chapter II, Section I, p. 7)

Table X gives the estimates made of the accelerative forces.

BANK ANGLE (DEG)	TRUE ACCELERATIVE FORCE (g)	MEAN ESTIMATED ACCELERATIVE FORCE (g)
10	1.02	1
18	1.05	1.02
30	1.15	1.19
40	1.31	1.32
50	1.56	1.62
60	2.00	1.95

Table X. Estimates of Accelerative Forces (Reference 10, Part V, Chapter II, Section I, p. 7)

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(c) PROPRIOCEPTIVE AND TACTUAL SENSES

The Proprioceptive Sense. As used here, "proprioceptive" is synonymous with "kinesthetic." The proprioceptive senses are those senses inside the body which are activated by movement or tension changes of body tissues, including the muscles. The stimulus of movement or tension may be due to voluntary movements, it may be due to the involuntary muscle movements produced to maintain posture when the vestibular and/or visual senses detect a change in position, or it may be due to anatomic changes produced by applied forces. As mentioned earlier, it may be true that the only way in which impulses from the vestibular mechanism affect conscious perception is by the indirect effect of stimulating the proprioceptive senses through reflex responses of the body to stimuli from the vestibule.

One of the main functions of the proprioceptive senses is to enable a human being to control his voluntary muscular activities even without the aid of vision. For instance, if a pencil is laid on a table, and a subject is given a brief look at its position, he can reach out and pick up the pencil with his eyes shut. Or he can tie his shoelaces while blindfolded. Or he can release a ball at just the right point in the arm's trajectory to aim it. Similarly, the forces which must be exerted to lift an object, say a typewriter, to a desired height are finely adjusted to the resistance offered.

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The only way in which these activities could be controlled is through the proprioceptive senses, and one of the effects of training and practice is probably the development of this ability to control such activities using these senses. After training, individuals are generally entirely unaware of the operation of this sensory system and, as mentioned earlier, conscious attempts to control these activities can actually impair performance.

Secondly, the proprioceptive system serves in the perception of changes in orientation and equilibrium, either by detecting those changes in the position of body members which are caused by external forces (for example, the sensation produced when an elevator suddenly stops) or by detecting those reflex changes in the muscle system which maintain posture.

The Tactual Sense. The receptors for the tactual sense are located in the skin and are activated by external stimuli. The tactual sense detects a difference in pressure between adjoining skin areas. It is obviously involved in the control of pressures exerted by a pilot and in the perception of stick or pedal forces. Furthermore, it probably also aids the flyer in detecting forces between him and his seat. Such a force would exist in a skidding or slipping turn because the resultant force of gravity and radial acceleration in an uncoordinated turn would be a component in a direction to dislodge him.

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The proprioceptive and tactal senses then serve a pilot in the following ways:

1. The perception of stick-feel
2. The unconscious control of the learned muscular activities involved in actuating the airplane controls
3. The perception of changes in position or dynamic equilibrium which are caused by movements of the airplane in flight

The principle receptors for the proprioceptive sense in the muscle system are located in the muscle spindles and Golgi spindles, the former located in striated muscles, the latter in tendons. Practically nothing is known of how they work, but it is assumed that they are stimulated by stresses.

The receptors for the tactal sense are found chiefly in the hair follicles and in certain capsulated end-organs located in the subcutaneous tissue, such as the Meissner corpuscles and the Pacinian corpuscles. It must be borne in mind that the term "tactal" is used here only in reference to pressure, not to temperature or pain which also have receptors in the skin. The capsulated end-organs are all capsules of fatty tissue inside which nerve endings branch out. The receptors in the hair follicles consist of nerve endings embedded in a hair bulb and encircling the hair roots. Certain free nerve endings in the skin also help in the perception of pressure, though they are usually associated with pain. Pressure is felt when a

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differential force deforms the surface of the skin. The difference in pressure between the point of contact and the surrounding skin upsets the neutral equilibrium which existed before the stimulus was applied; if the pressure is continued, however, the equilibrium is restored and the sensation of touch ceases (unless the pressure is accompanied by movement). This agrees with a previous comment that, according to one theory, the sensory system evidently had evolved to detect changes in the environment.

A considerable amount of data is available on pressure thresholds for various skin areas and on the time required for adaptation to pressure.

Tables XI and XII present some of this information selected from Reference 10.

REGION	MINIMUM PRESSURES WHICH COULD BE PERCEIVED (GRAMS/MM ²)
Tip of Finger	3
Back of Finger	5
Front of Forearm	8
Back of Hand	12
Back of Forearm	33
Thick Parts of Sole	250

Table XI. Pressure Thresholds for Various Parts of the Body (Reference 10, Part V, Chapter II, Section II, p.2)

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WEIGHT OF STIMULUS (MG)	ADAPTATION TIME (SEC)
50	2.42
100	3.82
500	6.01
1000	6.71
2000	9.52

Table XIII. Elapsed Time from Application of a Pressure to the Back of the Hand until No Sensation Was Felt
(Reference 10, Part V, Chapter II, Section II, p. 3)

Table XII is not very significant because of the low weights used. However, it documents the important phenomenon of adaptation to pressure and indicates clearly that the time required for adaptation increases with the pressure exerted.

No such specific data are available concerning thresholds for proprioceptors, chiefly because they are so difficult to isolate and to work with. But data are available concerning the functioning of the proprioceptive and tactual senses in situations encountered by pilots.

It was pointed out previously that these senses serve the pilot mainly by aiding in the perception of movement (changes in dynamic equilibrium or position) and in the perception and control of stick, wheel, and pedal forces or displacements.

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With reference to the perception of movement, it was mentioned that vestibular impulses could not be definitely asserted to enter conscious perception. Perhaps all that is consciously felt from change in static position or from a change in dynamic equilibrium (that is, a change in a linear or angular acceleration) is the accompanying proprioceptive sensations which are produced by reflex responses of the body and by the alterations of the positions of the viscera due to the variations of the resultant force on the body caused by the acceleration or the tilt. In the organization of this volume, data on the thresholds for perception of acceleration and tilt were presented in the section dealing with the vestibular senses, even though these senses by themselves may not be able to produce a conscious perception of acceleration or tilt. This was done because it is unanimously recognized that the vestibular senses are stimulated by acceleration and tilt regardless of what intervenes before conscious perception takes place.

With respect to the performance of the proprioceptive and tactual senses in monitoring the learned voluntary muscular movement of the pilot, much more information exists. W. O. Jenkins, in References 16, 17, and 18, reports on a thorough investigation he has made of the accuracy with which pilots and non-pilots can exert forces on the three types of controls found in aircraft: stick, wheel, and rudder pedals. Similarly Brown, Knauft, and Rosenblum, in Reference 3, have presented information on the accuracy with which displacements can be made.

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In the experiments described by Jenkins, a control stick was mounted in a cockpit mockup. The pressures exerted on this stick required very little deflection, and therefore stick displacements provided no cues. A means of recording this stick force was provided. The 20 pilots and 13 non-pilots who acted as subjects were allowed to practice exerting given forces until their performance was approximately correct. Then each subject was required to exert a designated force while blindfolded (to eliminate cues from the recording instrument). The designated forces were presented in a random fashion. In all, five designated forces were applied in each of four directions of exertion. At the end of a trial, the subject was told the maximum pressure he had applied. Each subject made 20 trials in each direction for each force. The results and the notation used are given in Table XIII.

The change in sign of CE indicates an important qualitative tendency: small forces tend to be overestimated and large forces to be underestimated.

The author states that the differences in directions did not give statistically significant differences in SD or CE . Therefore, the data from the next runs were tabulated without a breakdown of direction; see Table XIV which is self-explanatory.

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STANDARD PRESSURE (1bs)	PUSH			PULL			RIGHT			LEFT		
	SD $\frac{SD}{S}$ (1bs)	SD $\frac{SD}{S}$ (1bs)	CE (1bs)									
1	.16	.16	.07	.26	.26	.10	.20	.20	.08	.20	.20	.09
5	.48	.10	.13	.56	.11	.10	.49	.10	.09	.50	.10	.11
10	.88	.09	.14	.85	.08	.17	.66	.07	-.01	.91	.09	.05
20	1.34	.07	.08	1.34	.07	.08	1.50	.08	-.02	1.60	.08	.03
30							2.01	.07	-.20	1.98	.07	.07
40	2.42	.06	-.47	2.34	.06	.04						

Note:

S = Standard Pressure (i.e., the Designated Force)
 SD = Standard Deviation
 CE = Constant Error = Mean Attained Pressure - Standard Pressure

$\frac{SD}{S}$ = Difference Threshold

Table XIII. Accuracy With Which 20 Pilots Could Exert the Required Forces on a Stick in Various Directions after Practice and with Knowledge of Results (Reference 16)

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STANDARD PRESSURE (lbs)	(a) 20 PILOTS			(b) 13 NON-PILOTS			(c) 11 PILOTS (NO PRACTICE)			(d) 28 PILOTS (NO KNOWLEDGE OF RESULTS)		
	SD	$\frac{SD}{S}$	CE (1bs)	SD	$\frac{SD}{S}$	CE (1bs)	SD	$\frac{SD}{S}$	CE (1bs)	SD	$\frac{SD}{S}$	CE (1bs)
1	.21	.21	.08	.32	.32	.13	1.33	1.33	.49	.33	.33	.62
5	.51	.10	.11	.67	.13	.20	1.13	.25	.32	1.13	.23	1.46
10	.83	.08	.09	.99	.10	.22	1.47	.15	.22	1.53	.15	1.62
20	1.46	.07	.04	1.66	.08	-.01	2.64	.13	-.14	1.83	.09	.56
30	1.09	.07	-.07	2.18	.07	-.19	3.79	.13	-1.15	1.94	.06	-1.53
40	2.40	.06	-.22	2.61	.06	-.22	4.69	.12	-1.11	2.85	.07	-.03

(See Note on Table XIII)

Table XIV. Accuracy in Exerting Designated Forces on a Stick by:

- (a) Pilots with Practice and Knowledge of Results
- (b) Non-Pilots with Practice and Knowledge of Results
- (c) Pilots with no Practice
- (d) Pilots with no Knowledge of Results
(Reference 16)

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The standard deviation can be considered to be the least discernible difference in forces applied, and hence, according to Weber's Law, its ratio to S should be a constant. As usual, this only applies over a limited range of stimulus intensity: in this case SD/S decreases very rapidly as S increases to 10 pounds and then remains relatively constant for all groups. The large values at low pressures are ascribed to the subject's inability to distinguish force applied voluntarily from the force exerted by the weight of his hand resting on the stick. It so happens that the standard deviation for the group of pilots with practice and knowledge of results satisfies a linear equation, expressing the expected increase in SD with S :

$$SD = .23 + .06S$$

The scores of pilots are better than those for non-pilots, and the difference is statistically significant: according to the p -test, the probability that the difference in scores is due to chance is less than .01.

The same experiment was repeated using a wheel control, six standard pressures, and only fifteen trials for each pressure and direction. The results are given in Table IV.

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STANDARD PRESSURE (lbs)	RIGHT			LEFT			COMBINED		
	SD (lbs)	SD/S (lbs)	CE (lbs)	SD (lbs)	SD/S (lbs)	CE (lbs)	SD (lbs)	SD/S (lbs)	CE (lbs)
1	.22	.22	.13	.24	.24	.15	.23	.23	.14
5	.44	.09	.24	.45	.09	.22	.44	.09	.23
10	.66	.07	.26	.67	.07	.32	.67	.07	.29
20	1.22	.06	.25	1.17	.06	.30	1.20	.06	.28
30	1.86	.06	.28	1.51	.05	-.02	1.69	.06	.13
40	2.08	.05	.19	2.00	.05	.01	2.04	.05	.10

(See Note on Table XIII)

Table IV. Accuracy of Pilots in Exerting Designated Forces on a Wheel Control in Two Directions after Practice and with Knowledge of Results (Reference 16)

As might be expected, the standard deviation increases with the standard pressure. The Weber fraction, SD/S , is not a constant but decreases non-linearly until S reaches 10 pounds; from there on, the ratio SD/S is approximately constant (as it is for stick-type controls). The constant errors are the same for both directions up to 20 pounds; above that, leftward motions have lower values for CE (for these right-handed pilots). The difference in performance, as measured by the standard deviation and by the Weber fraction, between stick and wheel controls favors the wheel type control. But Jenkins found that the differences were not statistically significant at the 5% level, which means that the probability that the difference in performance was due simply to chance is greater than .05.

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Finally, the experiment was repeated using pedals from a rudder control. Since the weight of the pilot's foot on the pedals was 7 pounds, the standard pressure of 1 pound was omitted from the totals. The results are given in Table XVI.

STANDARD PRESSURE (lbs)	RIGHT PEDAL			LEFT PEDAL			COMBINED		
	SD (lbs)	SD S	CE (lbs)	SD (lbs)	SD S	CE (lbs)	SD (lbs)	SD S	CE (lbs)
5	.37	.09	.31	.50	.10	.25	.49	.10	.28
10	.68	.07	.19	.76	.08	.27	.72	.07	.23
20	1.04	.05	.26	1.12	.06	.42	1.08	.05	.34
40	2.12	.05	-.05	1.97	.05	.05	2.05	.05	0
60	2.83	.05	-.36	2.51	.04	.10	2.67	.04	-.13

(See Note on Table XIII)

Table XVI. Accuracy of Pilots in Exerting Designated Forces on Pedals after Practice and with Knowledge of Results (Reference 16)

At the same time, numerous British sources (References 5, 6, 12, 13, and 19), dealing with the problem of control design, have found that friction forces of 2 pounds for hand controls and 7 pounds for pedal controls improve the accuracy of an operator's performance with these controls. These friction forces reduce the

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effects of the following factors which tend to impair accuracy: (1) body-sway, (2) hand-tremor, (3) jolting, and (4) involuntary sag of the arm or leg. But friction forces in excess of 3 pounds for hand controls are not desirable because they do not improve the operator's performance and do contribute to his fatigue. It is the consensus, however, that no movement of a hand control should require less than 2 pounds of force and that no pedal movement should require less than 7 pounds of force.

Perhaps the most important conclusion from the investigation of proprioceptive and tactal perception of control forces is that Weber's Law holds for forces above 10 pounds. The greater the force which the pilot is exerting, the larger the change must be for him to perceive it as a change. Reference to this principle will be made later.

Another voluntary muscular activity which can be monitored by the proprioceptive senses is the displacement of a body member to a desired position. Reference 10 reports the results of an experiment performed by the authors of Reference 3 to determine the properties of this kind of movement. In this experiment, each subject was allowed to view an object, located at a certain distance from him, for 2.5 seconds; then he was required to move his right hand, in total darkness, to that point. Three different distances were used: 6 cm, 2.5 cm, and 40 cm. The results as given in Reference 10, were:

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1. Short distances were overshot; long distances were undershot (this pattern is already familiar).
2. The percentage errors were maximum for the shortest distance and decreased each time the distance was increased. (Weber's Law would suggest that eventually this percentage error should remain constant, but this was not observed.)

Reference 14 confirms the first result given above but also reports that the percentage errors in a similar experiment stayed within limits of from 5% to 10%. Finally, two German sources, reported by Orlansky, reached the same conclusion that short distances are overestimated and long distances underestimated. At the same time, they found that the average displacement error was close to 15%.

To conclude this section, some qualitative results concerning the effects of the position of controls and the direction of movement on the accuracy of control by human operators are included. These data were compiled from the literature by Orlansky, who presents this information as follows:

- I. In an experiment in which trained pilots were to keep a randomly moving pointer on a reference mark using airplane type controls, it was found that:
 - A. Hand controls are more efficient than foot (efficiency is defined to be the total time the pointer was on the reference).
 - B. For both stick and wheel controls, elevator movements (back and forth) are more efficient than aileron or rotary movements.

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- C. Stick and wheel efficiency are about the same.
- D. Changes in leg or arm angles from 105° to 135° do not affect efficiency but produce changes in comfort.

This experiment of course included visual control as well as proprioceptive, but the variables affected only the proprioceptive aspects, not the visual.

- II. Motion is most accurate at elbow height.
- III. Hand-tremor increases appreciably beyond 8 inches above or below the heart.
- IV. Performance is more accurate when visual cues are used in conjunction with proprioceptive than it is with proprioceptive cues alone.
- V. Positioning movements away from the body are more accurate than those toward the body.
- VI. The direction of movement of controls should be similar to the expected direction of the effect; this is particularly important in rapid adjustment.

Additional results taken from Hick and Bates (Reference 14) are:

- VII. The duration and force of a movement are less accurately judged than is its extent.
- VIII. Any position of the controls is satisfactory if they can be conveniently reached.

Section 4

SECTION 4 - THE PILOT AS AN ACTUATOR

This section deals with the pilot as an actuator. The motor responses the pilot makes in controlling an airplane can be divided into four categories: positioning movements, repetitive movements, static reactions, and continuous adjustments. In a positioning movement, the position of a body member, such as an arm or leg, is changed in response to a stimulus. There are numerous examples, such as a pilot extending his arm to push the control stick or extending his leg to push the rudder pedal. In a repetitive movement, a single discrete movement is rapidly repeated, as in turning a wheel. In a static reaction, a body member is held for a certain time in some position, perhaps exerting pressure or tension on some object; essentially, this kind of reaction is simply a particular kind of positioning movement. Finally, in a continuous adjustment, the pilot is called on to make varying movements in response to a varying stimulus, an example being the response made in a tracking task.

Repetitive movements will not be discussed in this volume. Continuous adjustments are the subject of Chapter III, where the aim is to develop mathematical models which will predict the pilot's response in a continuous control task. The remaining responses to be considered in this section are positioning movements and static reactions.

Section 4a

The accuracy with which pilots can make positioning movements and exert forces in static reactions was treated in the preceding section in connection with the sensory functions of the pilot. However, several other aspects of these motor responses should be considered, and these considerations are the subject of Section 4. In particular, Section 4a deals with the maximum forces which pilots can exert on stick, wheel, and rudder controls, and the variation in these maximum forces when the controls are in different positions; Section 4b presents the maximum rates at which the pilot can move the controls in positioning movements, including the case where there is a load on the controls; and Section 4c deals with the reaction time which always elapses between a stimulus to respond and the beginning of the response.

(a) THE PILOT AS A FORCE PRODUCER

In the past, the power supplied by the pilot's muscles was all that was available to operate the control surfaces of an airplane. The responses of the pilot in controlling the craft therefore had to involve the application of a force to a stick, wheel, or pedal, as well as a deflection of these controls. Indeed, pilots learned to fly by associating certain airplane responses with the application of certain forces.

However, in recent years, greater and greater speeds have increased the aerodynamic loads on the control surfaces and, as a result, have made it impossible for the pilot to supply all the power required to move these

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surfaces. Consequently, power-boosted or fully-powered control systems have been introduced; in the one case, pilots are required to supply only a portion of the power required; in the other case, none. The need for force in the pilot's response would seem to be eliminated in fully-powered control systems; but since he considers force cues necessary, they are supplied artificially. As a result, the pilot must still exert forces.

Data concerning the accuracy with which pilots can exert forces or discriminate between pressures have already been presented. Another question arises: What are the largest forces that pilots can exert? Answers to this question are given below.

But first it must be pointed out that the greatest forces required of a pilot in normal flight or under emergency conditions must be kept well below the maximum values. In normal operation, this is necessary to reduce fatigue and to maintain efficiency during flights which may be long and which may take place under adverse conditions, such as rough weather, when a great deal of attention to the controls is required. Under emergency conditions, such as a power control failure, it must be possible, even for pilots whose strength is below average, to control the airplane safely.

Maximum Control Forces. According to Orlansky (Reference 23), one of the main sources of data on the maximum control forces which pilots can exert is an NACA experiment in which only two pilots were tested; the maximum forces which

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could exert in various test situations were measured, and the lower value in each case determined the maximum force which pilots could be expected to produce. On the basis of these data, Orlansky estimated maximum control forces for various positions of the controls in a standard cockpit. The maximum stick and aileron forces (using the right hand only) were obtained (1) for various distances of the stick from the back of the seat and (2) for different lateral positions of the stick. (Since both these pilots were right-handed, the most favorable lateral position of the stick for push and pull motion was to the right of center.) Maximum rudder pedal force (using the right foot only) was estimated for three different distances of the pedal from the back of the seat. These values, taken from Orlansky, are presented in Tables XVII and XVIII.

Next, on the basis of data from many different sources (listed in Appendix A of Reference 23), Orlansky estimated the maximum forces which can be applied. Among these are forces actually exerted in flight tests, which may not, of course, be the maximum attainable. The estimates are given in Tables XIX, XX, and XXI.

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STICK POSITION: DISTANCE OF STICK FROM BACK OF SEAT	PUSH (LATERAL POSITION)			PULL (LATERAL POSITION)		
	MOST UNFAVORABLE	CENTER	MOST FAVORABLE	MOST UNFAVORABLE	CENTER	MOST FAVORABLE
	Back: 12 in.	30	39	59	24	24
Neutral: 19 in.	45	76	76	51	91	103
Forward: 24 in.	64	109	109	90	129	129
	PUSH (TO LEFT)			PULL (TO RIGHT)		
	EXTREME LEFT	NEUTRAL	NEUTRAL	NEUTRAL	EXTREME RIGHT	EXTREME RIGHT
	Back: 12 in.	46	32	30	26	26
Neutral: 19 in.	47	44	35	26	26	26
Forward: 24 in.	40	60	39	28	28	28

Table XVII. Estimates of the Maximum Stick and Aileron Forces which Can Be Exerted for Various Positions of the Stick (Reference 23)

RUDDER POSITION	DISTANCE FROM BACK OF SEAT	RUDDER FORCE
Back	31 in.	246
Neutral	34 3/4 in.	424
Forward	38 1/2 in.	334

Table XVIII. Estimates of the Maximum Rudder Forces which Can Be Exerted for Various Positions of the Rudder Pedal (Reference 23)

Section 4a

DISTANCE FROM BACK OF SEAT	TYPE OF CONTROL		
	WHEEL	STICK (RIGHT HAND)	STICK (BOTH HANDS)
10 in.	*Push: 160 lbs	*Push: 40 - 80 lbs.	
12 in.	Push: 150 lbs Pull: 115 lbs		
14 in.	Push: 155 lbs		
17 in.		*Push: 25 - 50 lbs	
18 in.	Push: 185 lbs Pull: 215 lbs	Push: 135 lbs	Push: 250 lbs
18 1/2 in.			*Push: 250 lbs
19 in.		Push: 145 lbs Pull: 115 lbs	Push: 220 - 255 lbs Pull: 225 lbs
21 in.	Push: 220 lbs Pull: 250 lbs		
24 in.	Push: 250 lbs *Pull: 300 lbs		
27 in.	Push: 185 lbs Pull: 275 lbs		
30 in.	Push: 110 lbs Pull: 250 lbs	--	

#Denotes Values Actually Recorded in Flight Tests

Table XIX. Maximum Stick Type Forces Estimated by Orlansky from Data from 12 Sources (Reference 23)

Section 4A

DISTANCE FROM BACK OF SEAT	WHEEL CONTROL			STICK CONTROL	
	ONE HAND ON SIDE	ONE HAND ON TOP	TWO HANDS	HIGH HAND	LOW HAND
12 in.	Pull: 35 lbs	Push: 57 1/2 lbs	Pull: 65 lbs Push: 75 lbs		
15 in.	Pull: 40 lbs	Push: 55 lbs	Pull: 85 lbs Push: 85 - 90 lbs		
18 in.	*Pull: 45 lbs	Push: 50 lbs	Pull: 82 1/2 lbs Push: 100 lbs		
19 in.				*Pull: 40 - 55 lbs *Push: 35 - 45 lbs	*Pull: 120 lbs
21 in.	Pull: 35 lbs	Push: 35 lbs	Pull: 75 lbs Push: 87 1/2 lbs		
24 in.	Pull: 35 lbs	Push: 32 1/2 lbs	Pull: 75 lbs Push: 85 lbs		
27 in.	Pull: 25 lbs	Push: 27 1/2 lbs	Pull: 60 lbs Push: 70 lbs		
30 in.	Pull: 20 lbs	Push: 25 lbs	Pull: 45 lbs Push: 47 1/2 lbs		

#Denotes Values Actually Recorded in Flight Tests

Aileron Force: Pull, to the Right
 Push, to the Left

Table XI. Maximum Aileron Type Forces as Estimated by Orlansky from
 Data from 8 Sources (Reference 23)

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DISTANCE FROM BACK OF SEAT	TYPE OF CONTROL	
	RUDDER PEDAL	TANK PEDAL
Neutral: 34 3/4 in.	400 - 500 lbs (Average of 2 Studies)	
35 - 39 in.	* 90 - 500 lbs	
40 in.		700 lbs (Average Maximum of 38 Subjects)

Table XXI. Maximum Pedal Forces Estimated by Orlansky from Data from Eight Sources (Reference 23)

(b) THE PILOT AS A MOTION PRODUCER

This section considers the speeds with which the pilot can move the controls, when he is acting as an actuator, including the variation of these speeds when the control is being moved against a load. It is assumed that the pilot can reach all the positions required in these movements.

The following information on rates of motion was taken from Orlansky (Reference 23) who selected it from various experiments; it is especially appropriate because the data are concerned with movement of airplane controls and not with a laboratory situation. One such experiment, performed by De Beeler, measured the maximum rates at which each of nine pilots could push or pull a control stick as the load per unit displacement was varied. The lowest of these maximum rates for the nine pilots can be taken as a conservative estimate of the rates of stick motion which pilots in general can be expected to produce.

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As the load increased from 0 lbs/in. to 33 lbs/in., the rate of pulling decreased from 75 in./sec to 23 in./sec; at the same time, the rate of pushing decreased from 105 in./sec to 33 in./sec. It is interesting that pushing speeds were higher than pulling speeds.

Another measure of rates of control motion is provided by a British study which found that the average maximum rate of stick pulling was 63 in./sec as the load varied from 10 lbs/in. to 190 lbs/in.

Orlansky also examined flight test records obtained from maneuvers in which pilots were instructed to make their utmost effort to obtain full elevator deflection in .2 second. Under differing conditions, the loads which were pulled varied, but the deflection, 6 to 8 inches, changed only slightly. Table XXXII shows the maximum force for each pull-up, the average speed of the stick, and the time required for each full stick deflection.

PULL-UP	MAXIMUM STICK LOAD (LBS)	AVERAGE RATE OF STICK MOTION (IN./SEC)	TIME FOR FULL DEFLECTION (SEC)
1	35	51.85	.162
2	74	15.58	.475
3	77	11.00	.600
4	97	10.27	.750

Table XXXII. Rates of Stick Movement in Flight Test Pull-Ups Under Various Loads (Reference 23)

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Orlansky's conclusions are:

1. Rate of control stick motion decreases as the load against which the stick is being moved increases.
2. For a 35 pound load, the maximum rate of stick movement can be taken as 50 in./sec. (The range is from 10 to 75 in./sec)
3. Pushing a stick can be approximately 25% faster than pulling,

Reference 10* contains data concerning rates of positioning movements, some of which amplify Orlansky's conclusions, but in laboratory situations. One important principle established by data in Reference 10* is that as the distance involved in a positioning movement is increased, the subject increases the speed of his movement, so that the time required for the response remains nearly unchanged. To be specific, results given in Part VI, Chapter II, Section II, page 13 indicate that as the distance moved in a positioning movement increases by a factor of 16, the time required for the movement is increased only by a factor of 2.5. Furthermore, data on page 15 indicate that if distance is doubled, the time required is increased only by 15%, and if the distance is trebled, the time required is increased only by 25%.

Orlansky's Conclusion 3 is partially substantiated by another experiment reported in Reference 10*, where it was found that the average speed in a positioning movement involving the extension of an arm (pushing) is approximately 9% to 14% greater than it is for a flexing movement (pulling), depending on which arm is used. Except for this, there seems to be little variation of speed of movement with direction of movement.

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The greater speed of pushing as compared to pulling applies only to that part of the positioning movement referred to as the primary movement. The primary movement is the initial, relatively fast movement which brings the body member near the desired position, but which generally leaves a small error, either an undershoot or an overshoot. The primary movement is followed by a secondary movement, which is relatively slow and which reduces the error left at the end of the fast portion of the response. As will be pointed out in Chapter III, this secondary movement is frequently oscillatory in nature. For secondary movements, according to Reference 10*, average speeds of movement are very slightly greater for pulling responses than for pushing responses, just the opposite from the situation for the primary movement.

Reference 10* also presents data in Part VI, Chapter II, Section II, page 15 indicating that in a positioning movement where a change of direction is involved in the response, about 15% to 24% of the total time is used in stopping the movement in one direction and starting it in another; during this time there is no movement at all. Of course, this makes the average speeds for such movements lower than for movements of the same distance but in one direction.

The decrease in speeds of movement with increasing loads is well-substantiated in Reference 10*.

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(c) REACTION TIME

Reaction time is defined to be the time which elapses between the presentation of a stimulus to a subject and the beginning of the response to this stimulus. The subject's response to the stimulus will then be split into two distinct phases: (1) the reaction time, during which no movement is made and (2) the movement time during which the response is made. If the time required for the subject to make the response following the stimulus is called the response time, then

$$\text{Response time} = \text{Reaction time} + \text{Movement time}$$

Reaction times may be separated into two categories: simple reaction times and complex reaction times. Simple reaction times occur in situations where the subject makes a unique, predetermined response to a specific stimulus. Complex reaction times occur when the subject must discriminate either between several stimuli or between several possible responses, or both.

Most laboratory measurements of reaction times, whether simple or complex, are characterized by the fact that the movement made in the response is deliberately kept small. The purpose of this is to make the movement time negligible, so that the reaction time can be taken to be equal to the response time, which is easier to measure. For instance, typical responses made in laboratory experiments are pressing a key or a button with a finger, or lifting a finger from a key. This activates a signal of some sort,

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and the elapsed time between this signal and the presentation of the stimulus, which is really response time, is easier to measure than the reaction time, which is the elapsed time between the stimulus and the instant when the subject begins to move his finger. As long as the subject does not have to move his finger very far, it can be assumed that the movement time is zero and therefore the response time is equal to the reaction time. Obviously, in the responses made by a pilot, longer movements are involved and perhaps the application of large appreciable forces; consequently, movement times will not be negligible and response times in control movements will be larger than the reaction times measured in the laboratory and presented in the tables below.

Reaction time is not a function only of the receptors and effectors involved; it also varies with all the following variables:

1. The sense which is stimulated. (In the case of the eye, the reaction time depends on which portion of the eye receives the stimulus.)
2. The effectors used in making the response.
3. The intensity of the stimulus (which is assumed to exceed the threshold level of perception for the sense affected).
4. Whether or not the subject is given a warning before the stimulus is presented; and if so, the duration of the period between warning and stimulus.
5. Whether the reaction is simple or complex.

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1. Variation of Reaction Time with the Sense Stimulated. See Tables XXIII and XXIV. As a general rule, the senses can be ranked in the following order of increasing simple reaction time: auditory, tactual, visual, and proprioceptive. As for the visual sense, reaction times can be decreased by keeping the stimulus in the direct line of sight, according to the data of Table XXIV.

2. Variation of Reaction Time with the Effectors Used in the Response. See Table XXV. Reference 10 reports that the differences in reaction time between the right and left hands are statistically significant; the same is true with the right and left feet. It is interesting to note that in a study designed to measure the response time required for applying an automobile brake, mean values of .514 and .524 second were obtained for auditory and visual stimuli respectively. This is approximately three and one-half times as long as the reaction time for pressing with the right foot, given in Table XXIV, due to the inclusion of movement time.

3. Variation of Reaction Time with the Intensity of the Stimulus. See Table XXVI. As would be expected, the closer a stimulus is to the threshold level for a given sense modality, the longer is the reaction time to that stimulus. The converse statement that increasing stimulus intensity should shorten the reaction time is true up to a certain intensity level, beyond which no further decrease in reaction time occurs.

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These statements are verified both in Reference 10 and in the "cross-bar" experiments by Bates which were discussed previously in the section on visual acuity (3a1). Figure 6 shows that the minimum complex reaction time for selecting the longer of two lengths in Bates's "cross-bar" experiment is .4 second; no matter how large the stimulus intensity (percentage difference in the two lengths) was made, the reaction time could not be decreased below .4 second.

Table XXVI, taken from Reference 20, shows the increase in reaction time as a visual and an auditory stimulus are decreased in intensity. The data also reflect another interesting principle, namely that reaction times to the onset and to the end of a stimulus are very nearly the same.

Reference 10* reports on another experiment whose results are in agreement with these principles. In this experiment the subject watched a region which was illuminated at a certain intensity, I foot-candles. Then the intensity of illumination was increased or decreased by ΔI foot-candles (the change ΔI was sufficiently large to be above the threshold level for visual perception of illumination change). The subject was to respond as soon as he perceived the change by pressing a key. Four levels of illumination, I , were used; and eight changes, ΔI , were made for each level. Each subject made twenty responses at each illumination level. The results are shown in Figure 7.

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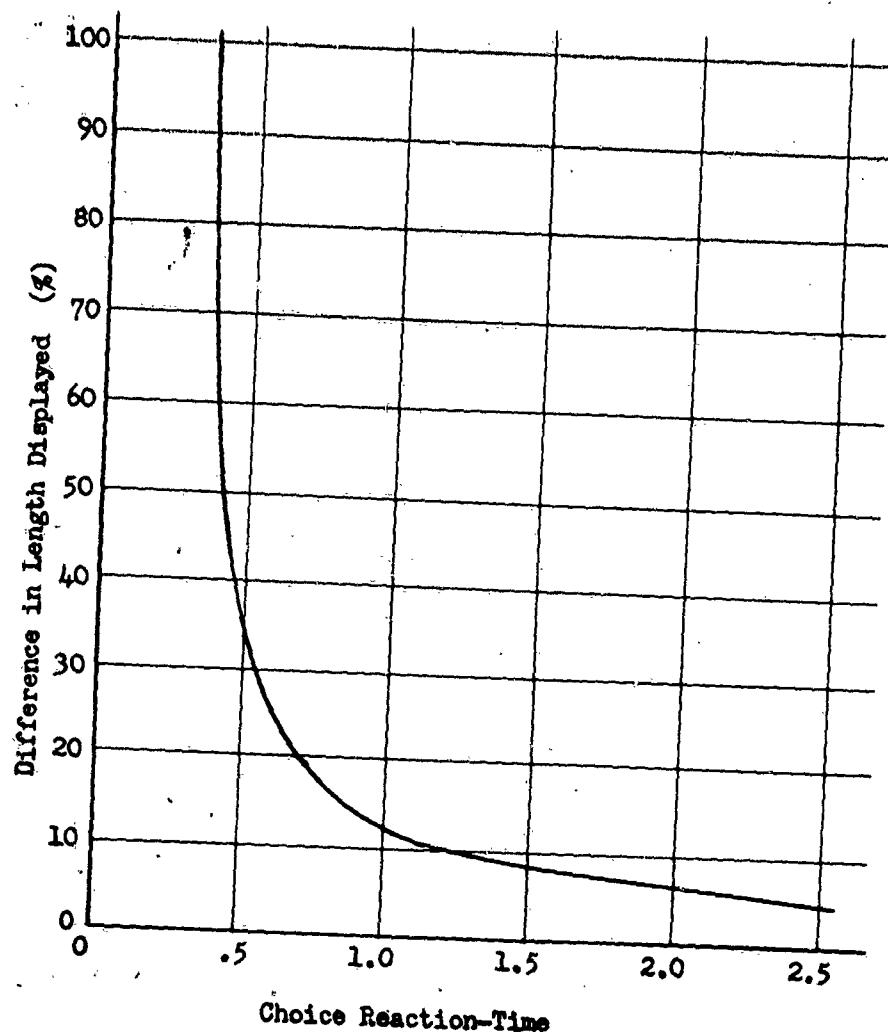


Figure 6. Variation of Choice Reaction Time
with Stimulus Intensity (Reference 2)

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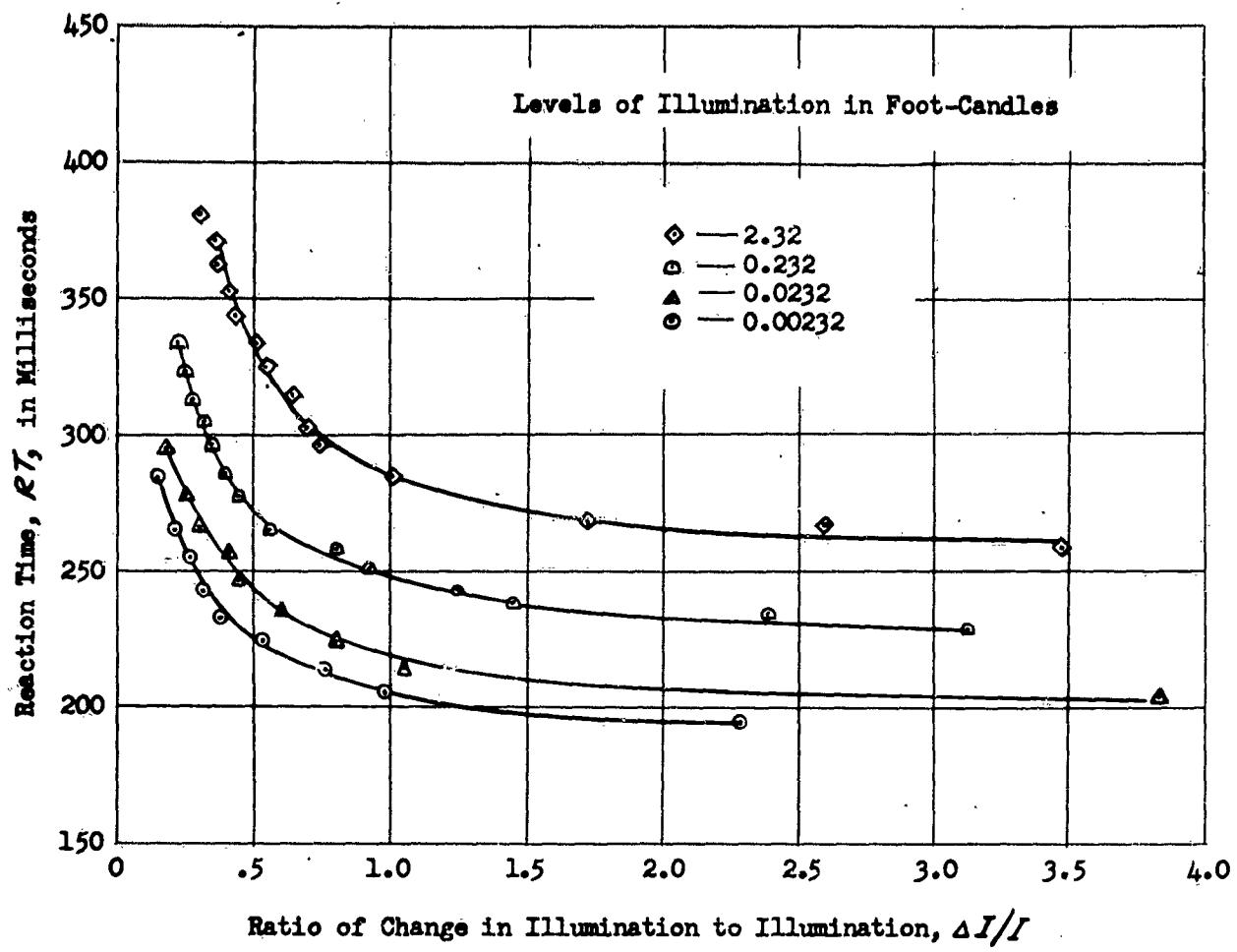


Figure 7. Relationship Between Reaction Time and Stimulus Intensity (Reference 10*, Part VI, Chapter II, Section II, p. 7)

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The two principles established are: (1) When the change, ΔI , is varied in such a way that the ratio $\Delta I/I$ is kept constant, the reaction time decreases as the illumination level, I , increases. In other words, as the intensity, I , increases, the same percentage change in intensity causes shorter reaction times. (2) For any one level of illumination (I fixed), the greater the change in illumination intensity the faster the reaction time was -- up to a certain point. For each level, I , there appears to be a minimum reaction time for perceiving the change, no matter how large the change may be. This agrees with the results of the experiment described by Bates and mentioned above.

While it is difficult to generalize from this experiment to situations involving other senses, it is reasonable to assume that, qualitatively, principles (1) and (2) above are valid for other senses. Indeed, the existence of a minimum reaction time is borne out by the results of tracking studies made by Searles and Taylor and reported in Reference 10*. In these studies a subject was trying to follow a moving line with a pencil point. The line made sudden step displacements to the right or to the left, of widely-varying magnitude. In the course of these studies, more than 3000 responses were made. The mean reaction time obtained was .257 seconds, and Reference 10* states that the reaction time was apparently independent of the direction or magnitude of the step. This was confirmed in another experiment. The explanation is that all the steps were of sufficient size that any increase in size could not shorten the reaction time. (See Reference 10*, Part VI, Chapter II, Section II, p. 3.)

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It is also to be expected that if several stimuli, all calling for the same response, are presented simultaneously, the subject's reaction time will tend towards the shortest reaction time for the individual stimuli. Thus if a visual stimulus, which is relatively slow, is accompanied by a tactual stimulus, which is relatively fast, reaction time will be reduced. The two stimuli together act as a more intense stimulus.

SENSE STIMULATED	SIMPLE REACTION TIME (SEC)		SRT SOURCE 2
	MEAN	RANGE	
Auditory	.192	.121 - .432	.153
Visual	.289	.190 - .476	.174
Vestibular			
a) Stimulus: Start of Rotation	.516	.190 - 1.450	
b) Stimulus: Change Direction of Rotation	.722	.240 - 1.790	
Tactual			.170

Table XXXIII. Variation of Simple Reaction Time with the Sense Stimulated: Response Was To Press a Key or Button (Reference 10*, Part VI, Chapter II, Section II, p. 3.)

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DEGREES OF VISUAL ANGLE FROM FOVEA	SIMPLE REACTION TIME			
	NASAL SIDE		TEMPORAL SIDE	
	LEFT EYE	RIGHT EYE	LEFT EYE	RIGHT EYE
0	.185	.185		
3	.190	.192	.192	.190
10	.187	.190	.194	.192
30	.193	.192	.197	.196
45	.206	.207	.214	.216

Table XXIV. Effect of the Retinal Position of a Visual Stimulus on Simple Reaction Time (Reference 10, Part VI, Chapter II, Section I, p. 10)

RESPONSE	REACTION	
	AUDITORY STIMULUS	VISUAL STIMULUS
Press with Right Hand	.147	
Press with Left Hand	.174	
Press with Right Foot	.144	
Press with Left Foot	.179	

Table XXV. Variation of Simple Reaction Time with the Part of the Body Used In The Response (Reference 10, Part VI, Chapter II, Section I, p. 9)

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STIMULUS	RELATIVE STRENGTH	SIMPLE REACTION TIME TO:	
		ONSET OF STIMULUS	CESSATION OF STIMULUS
Visual	Strong	.162	.167
	Weak	.205	.203
Auditory	Medium	.119	.121
	Weak	.184	.182
	Barely Perceptible	.729	.745

Table XXVI. Variation of Simple Reaction Time
with Changing Stimulus Intensity
(Reference 20)

4. The Effect of a Warning Signal on Reaction Times. See Tables XXVII and XXVIII. References 10 and 14 use the data in Table XXVII to make certain points. Reference 10 uses them to illustrate the variation of effectiveness of a warning with the length of the foreperiod (the foreperiod being the time between warning and stimulus). Clearly, decreasing the foreperiod from 4.0 to 1.0 seconds enables the subject to reduce his reaction time, the differences all being statistically significant. On the other hand, Reference 14 is concerned with the much longer reaction time when the interval between stimuli is only .5 second. This relatively large value is taken by the authors as indicating a refractory phase. It is thought that following the warning stimulus there is a short period during which a second stimulus to respond cannot take effect. (Such a refractory phase is known to exist for individual nerves and effectors as was pointed out in Section 2 of this chapter. The question here

is whether such a refractory phase exists for a whole sense modality, or whether the smoothing effect of the numerous connectors eliminates the effect of the refractory phases of the individual receptors and effectors.) To substantiate the claim that a refractory phase does exist in simple reactions, one of the authors, Hick, in Reference 11, includes the data reproduced in Table XXVIII. It is seen that when intervals of two or three seconds exist between stimuli, the reaction times, both mean and minimum, are constant. But shortening the interval between stimuli to one second causes both the minimum and mean reaction times to be considerably increased. These data are all based on the reaction of one individual in many trials, and it is therefore impossible to ascribe statistical significance to the differences, but the authors claim that the variation is typical.

INTERVAL BETWEEN STIMULI (SEC)	MEAN SIMPLE REACTION TIME (SEC)
.5	.335
1.0	.241
2.0	.245
4.0	.276

Table XXVIII. Effect of a Warning Signal on Simple Reaction Time (Reference 10*, Part VI, Chapter II, Section II, p. 9; Reference 10, Part VI, Chapter II, Section I, p. 4, and Reference 14)

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	INTERVAL BETWEEN STIMULI		
	1 SEC	2 SEC	3 SEC
Mean Reaction Time for All Stimuli	.275	.244	.244
Minimum Reaction Time for All Stimuli	.206	.175	.175

Table XXVIII. Variations in One Individual's
Reaction Time with Changing
Intervals Between Stimuli
(Reference 11)

The question of whether a refractory phase exists has important ramifications for the mathematical treatment of the response of a human pilot and will be returned to in the next chapter. Results presented there show at least that the reaction time to the second of two stimuli increases steadily as the interval between the two stimuli decreases, regardless of whether the refractory phase exists or not. One implication is that if a stimulus to stop or change the direction of a movement follows closely upon the stimulus which caused the movement, then the time to stop or change direction will be longer than the time to begin it.

Reference 10* also presents data which show that after a subject has been conditioned by practice to expect an interval of a certain length between stimuli any change in the length of this interval will increase his reaction time to the second stimulus.

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5. Reaction Times for Simple and Complex Situations. See Table XXIX. The effect on reaction time when the subject must make a discrimination between stimuli and then select the appropriate response is shown in the following experiment, performed by Lemmon, and reported in Reference 10. A subject held a finger on each of two keys, one to the right and one to the left. He faced a panel of electric light bulbs, some of which were on the right of the panel and the rest on the left. In the first part of the experiment, one of the bulbs would light and the subject's response was to lift his finger from the key on the same side as the lighted bulb. This involved a choice based on a sensory discrimination as to which side the lighted bulb was on; this pattern of choice is referred to below as 1 or 1.

In the next part of the experiment, the problem was changed so that different numbers of bulbs would light on the two sides, and the subject's response was to lift his finger from the key on the side with more lights. This problem was presented in various degrees of complexity, so that the subject had to discriminate between 1 vs. 2 lights, 2 vs. 3 lights, 3 vs. 4 lights, and 4 vs. 5 lights.

The results, presented immediately below, show that the reaction time increases with increasing complexity of the sensory discrimination.

Pattern of Choice	1 or 1	1 vs. 2	2 vs. 3	3 vs. 4	4 vs. 5
Reaction Time (Seconds)	.290	.473	.566	.656	.741

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Orlansky states that if conscious judgment of the stimulus and response must be made, reaction times of from 1 to 2 seconds may be considered fast.

In connection with complex reaction, Reference 10 also describes an experiment which relates directly to a problem involved in flying. In this experiment, twenty experienced pilots were put through three minutes of disorientation (blindfolded) in a C-45. Then a standardized maneuver lasting 30 seconds was carried out, and the pilots were required to put the airplane back on straight and level flight as quickly as possible, either by instruments or by contact flight. Table XXIX gives the results. Although not explained in Reference 10, "comprehension time" presumably refers to the interval between the time a pilot was told to recover and the time he began the required maneuver, i.e., the interval during which he determined what the situation was and decided upon a course of action. The lower comprehension time for contact flying than for instrument flying is statistically significant at the 2% level (i.e., the probability that the difference could be attributed to chance is less than .02), whereas the lower recovery time is significant only at the 10% level.

Table XXX presents the reaction times (more precisely, the response times) which are required for a subject to focus his sight successively on objects which are alternately near to him and far from him (22 inches and 43 feet), or both far from him, or lastly, both near to him. The considerable increase in time required to refocus at different distances over that required for refocussing at the same distance can become significant in estimating a pilot's reaction time in certain tasks, e.g., landing. (See Section 2a.)

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	COMPREHENSION TIME (SEC)	RECOVERY TIME (SEC)	TOTAL
Mean for Contact Recovery	1.35	7.86	9.21
Mean for Instrument Recovery	1.55	9.46	11.01

Table XXIX. Comparison of Two Complex Reaction Times
for an Airplane Maneuver (Reference 10,
Part VI, Chapter II, Section I, p. 6)

FIXATION	MEAN REACTION TIME PER FIXATION	STANDARD DEVIATION	RANGE
Binocular Alternate	1.065	.205	.77 - 1.89
Left Eye Alternate	1.235	.300	.70 - 2.30
Right Eye Alternate	1.195	.340	.70 - 2.90
Binocular All Near	.900	.155	.50 - 1.45
Binocular All Far	.840	.220	.50 - 1.78

Table XXX. Reaction Time to Fixate on Objects at
Different Distances (22 Inches for Near
Objects, 43 Feet for Far) Reference 10,
Part VI, Chapter II, Section I, p. 10)

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According to the definition of simple reaction time, the effect of practice on simple reaction times should be nil, unless there are warning cues which the subject can become aware of through experience. This is pointed out by Hick and Bates in Reference 14. However, for complex reaction times, practice can definitely produce improvement, at least up to a certain point, since the subject can learn from practice to make the necessary discriminations between stimuli and/or responses more quickly.

Other variables affecting reaction time may be mentioned briefly. First, the age of the subject is very important. After the age of twenty, reaction times increase. Even among men of a single age group there is considerable variability in reaction time data. In a sample of men between twenty and thirty years old, the mean reaction time, as reported in Reference 10, was .22 second (visual stimulus), but the standard deviation was .033 second, which indicates considerable scatter in the data. This variability is partially confirmed by the large ranges listed in the data of Table XXXIII.

CHAPTER III

APPROXIMATE METHODS FOR PREDICTING THE RESPONSES OF A HUMAN PILOT

SECTION 1 - INTRODUCTION

This chapter presents the results of the most important attempts that have been made toward formulating approximate transfer functions to describe the simpler responses of human pilots or toward developing computer techniques for simulating those responses. As pointed out in Chapter I, it is assumed that the readers of this volume are familiar both with servomechanisms theory and with analog computer techniques. Therefore, no definition of a transfer function will be included, and wiring diagrams for analog computer circuits will be presented without explanation.

The first attempts to develop a transfer function for a human operator of a control mechanism were made in connection with the synthesis of devices for controlling guns under the direction of human gunners. It was apparent that the gunner was part of a closed loop system: in response to an error signal provided to him by the gunsight and consisting of the angular difference between the positions of the target and of the gun, the gunner actuated the gun

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control mechanism to move the gun. To design the gun control so that the performance of the whole system would be as efficient as possible, it was necessary to evaluate the closed loop response of the system to various types of target movement, with various controls. Of course, this closed loop response was affected by the gunner's response. Since the easiest way to make such a closed loop analysis is to have a transfer function for each of the components, several writers proposed transfer functions to represent the gunner himself. Among these writers are Phillips (Reference 15), Ragazzini (Reference 27), Russell (Reference 23), and Hick and Bates (Reference 14).

A similar situation confronts the flight control system designer. He is dealing with a closed loop system comprising the airframe, the human pilot, and the flight control system. Here also, the pilot senses errors from desired flight conditions and actuates the control system to eliminate these errors. The design of the flight control system must enable him to perform his stability and control functions as efficiently as possible. Of course, this requires a closed loop analysis of the responses of the whole system to transient disturbances and to inputs from the control surfaces or throttle. Omitting any component of the system from the analysis leads to inaccuracy, and therefore it would be desirable to have a transfer function to represent the pilot response in stabilizing and controlling the airplane. The most thorough and

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fruitful investigations directed toward establishing such a transfer function have been made by R. Mayne and his associates at the Goodyear Aircraft Corporation; they report their findings in References 9, 21, 25, and 26. The laboratory tests made in the Goodyear studies used only visual stimuli in order to simplify the experiments, whereas in actual flight, a pilot receives additional stimuli through his proprioceptive and vestibular senses. Also, in these laboratory studies, the pilot's whole attention was fixed on one task, that of stabilizing the simulated airplane in pitch, whereas his attention in actual flight could not be so undivided for so long.

In order to provide other stimuli to the pilot, Cheatham describes in Reference 4 an experimental setup in which the pilot, whose task was to control simulated lateral motions, was actually moved in a chair as he would be in flight, thus permitting proprioceptive, vestibular, and visual perception of his condition. But here too, the pilot's task was one-dimensional; that is, he was only controlling a single degree of freedom.

One way to eliminate this one-dimensionality, both in stimulus and in the task to be performed, would be to determine the pilot's frequency response from his performance of certain maneuvers in flight tests, and from this frequency response, determine an

Section 1

approximate transfer function. The results of an attempt to find such an approximate transfer function are described in Reference 1, but they turn out to be so varied and so specifically related to the maneuver, to the airplane, and to the control being used, that they appear to be of little use in determining a transfer function. However, the results may be useful in comparing pilots' abilities to fly a particular kind of airplane.

The purpose of such a transfer function is, of course, to determine analytically the response of a human operator in the performance of some task. The task may be of the continuous adjustment type, as when a man drives a car along a winding road, or it may require only a certain positioning response from time to time, for example when a pilot, trying to maintain a certain heading, perceives an error in heading from time to time and deflects the controls in order to turn to the desired heading. In either of these cases, if the stimulus from the environment (or at least an idealized version of it) could be specified as a function of time, then a transfer function for the human operator would enable the subject's response to be specified as a function of time. Such transfer functions of course cannot describe higher-level, decision-making functions of the human operator, but they may describe those responses he has learned to make to stimuli he expects to encounter in performing the task for which he is trained.

Section I

For example, there is some hope that it is possible to obtain a transfer function specifying the elevator deflection that a trained pilot will produce in response to a sharp wind-gust of the type encountered in flying, but there is no hope that a transfer function could predict the pilot's response when some emergency necessitates a reasoned decision about the proper course to follow, especially if the decision has emotional connotations for the pilot.

Even if the attempt to obtain transfer functions is limited to situations which have become routine for the pilot through training, certain major difficulties make it impossible to determine a unique transfer function. In the first place, the wide variability in reaction time and thresholds for sensory perception among different individuals means that a proposed transfer function must include several parameters which can be varied to account for these individual differences. This in itself is not too serious a drawback: a flight control systems designer could use mean values for these parameters and then vary them to cover the expected range of values. But as will be shown, given the same stimulus, three different pilots may respond in three different ways.

The second difficulty is that a normal individual's response to the same stimulus varies considerably from time to time. For instance, as the pilot's motivation or attention varies, he may ignore stimuli which ordinarily would cause a response. Thus the pilot's threshold is not constant for a given stimulus. Furthermore, numerous studies have shown that a pilot varies his gain, increasing it when necessary, or decreasing

it when he is not certain about what to do or when he is simply nonchalant. Another source of variation in an individual pilot's response is his ability to predict. He may predict in various ways: he may use simple, linear extrapolation, or he may, after being exposed to a varying stimulus for a time, be able to predict completely its future course.

The third source of difficulty, and the most severe one, is that a transfer function which adequately determines the pilot's response to one type of input, say two frequencies, will not be valid for a different type of input, say one frequency. This will be shown later. For any linear system, the transfer function, by definition, is independent of input.

Except for the case of the classical "dead-man" responses, which can be described by a linear model, the effect of multiple inputs cannot be determined by a single equation. Among those nonlinearities are the following characteristics which were discussed in Chapter II: the reaction-time delay, during which no response at all is made; the threshold for perceiving the stimulus; the tendency for pilots to underexert when trying to modulate large forces or displacements; the tendency to overexert when performing tasks; sensory illusions; and the upper bounds to motion which pilots can produce. There is some evidence that there is some evidence that the range effect, in which a pilot, after responding

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to a number of stimuli of roughly the same intensity, will respond in the same way to a new stimulus of a much different intensity; and finally a random jerkiness which is found superimposed on human responses.

The conclusion is that it is impossible to represent a human pilot by a single linear transfer function, even subject to the restriction of dealing only with routine, learned responses. All the experiments conducted to investigate pilot response have been made subject to the restriction that the pilot was engaged in controlling only a single degree of freedom. There is still hope that a set of transfer functions with variable parameters may be developed which can approximate within satisfactory limits the pilot's response in certain specific tasks. The experiments to determine such approximations have all been conducted in situations during which the pilot was engaged in controlling a single degree of freedom and was consequently called upon to make only one type of response; therefore these approximate transfer functions cannot be assumed applicable to situations where the pilot is controlling several variables at once. This means that these transfer functions cannot necessarily be used to predict the pilot's response in complicated maneuvers, such as landing or making coordinated turns. However, it is felt that they can be valid for stability investigations,

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for example in stabilizing the pitch of an airplane in gusty weather, or in controlling a yawing or rolling oscillation. They may also be valid for use in simple one degree of freedom control problems, such as that resulting when a pilot pulls out of a dive or enters a climb.

When it is agreed that the only approximate transfer functions expected will be for one-dimensional control tasks or for stabilizing one degree of freedom despite input disturbances, the question still remains as to the correlation of the transfer function with the type of input disturbance. As pointed out above, the nature of the pilot's response will change as the input varies.

In this chapter, the pilot's response to four types of inputs will be considered: single steps, sequences of steps (perhaps in opposing directions), simple sine waves, and finally, random-appearing functions. The content of the chapter is a discussion of a human being's response to those four types of inputs, and to a presentation of the transfer functions, if any, which have been proposed for those inputs. The situations for which some of them were developed are not always pilot control of an airplane; for example, some of them were developed in gun-tracking studies. But it can be assumed that these functions are general enough so that they also describe pilot response to similar types of inputs.

With reference to a human operator's response to random-appearing disturbances, the inaccuracies in trying to obtain this response from a transfer

Section 2

function are relatively large. On the other hand, the Goodyear studies have developed an analog computer network to simulate the pilot's response to random inputs, which has proved reliable. This computer network is as easy to use as any transfer function and much more accurate.

Tustin (Reference 30) and North (Reference 22) have assumed that the operator's response to random inputs has a linear component and a random component, and they have studied this random deviation from a linear response using techniques for analyzing stochastic processes. This work will not be included here, but can be studied in the references mentioned.

SECTION 2 - THE OPERATOR'S RESPONSE TO VISUAL STEP INPUTS

Figure 8 shows typical responses to visual step inputs in an experiment, reported by Mayne (Reference 25), in which subjects were to follow a line moving on recording paper and visible through a narrow slit. In (b) and (d), the visual input ended at the position indicated. The result shown in (a) is typical. Similar responses have also been observed by Taylor in an experiment in which subjects tracked a target by moving a stick similar to those used in aircraft. The target was a dot seen against a vertical line on an oscilloscope. As the dot jumped to the right or left, the subject was to move the stick to return the dot to the vertical line as quickly as possible. Inspection of the figures reveals that the response can be separated into two phases: first, there is a dead portion lasting a little over .2 second, during which the subject makes no movement at all; after that, there is what Mayne (References 9, 21, and 25) calls the

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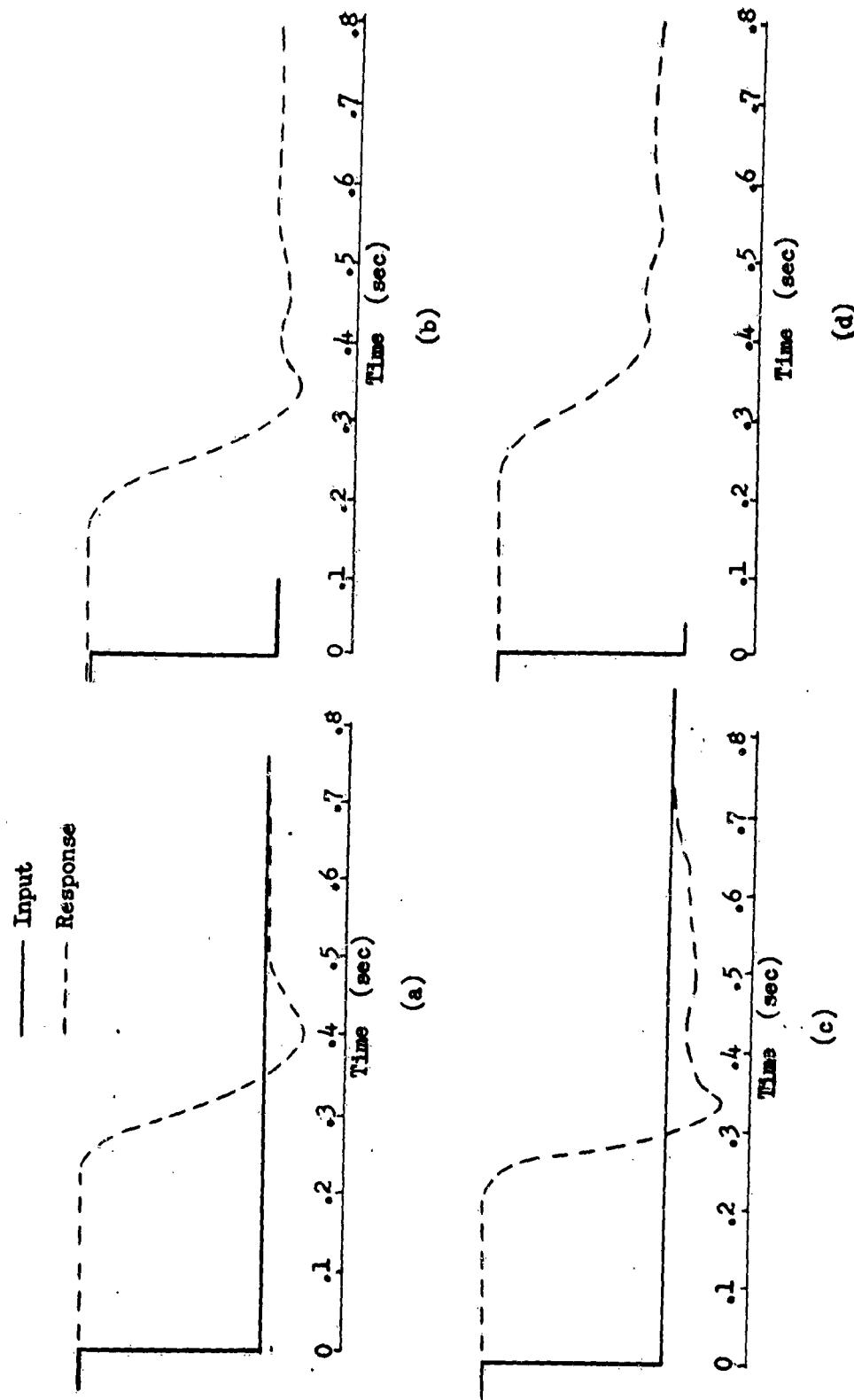


Figure 8. Typical Responses in Following Step Displacements
of a Moving Line (Reference 25)

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dynamic portion of the response, during which the subject moves relatively quickly (the primary movement of this positioning response) and ends with a small error; he then moves more slowly toward the new position of the line, eliminating the error (the secondary movement).

The duration of the dead portion of the response, which varies from a little less to a little more than .2 second in the cases shown in Figure 8, is within the range of simple reaction times to visual stimuli given in Table XXXIII but is somewhat below the mean given there. Also, the duration of the dead portion is apparently lower than the .257 second found in a similar problem discussed in Chapter II, Section 4c2. The dead portion of the response is called the reaction-time delay. Both Taylor (Reference 29) and Mayne (Reference 21) state that during this time a certain signal is being computed in the higher centers of the central nervous system and set into the effectors, and that the time required for this computation and setting is the principal component of reaction time.

It is certainly true that a movement response to a visual stimulus can be executed without continual visual control of the movement. This is shown by (b) and (d) of Figure 8, in which the line to be followed was suddenly terminated after the step occurred, but the proper response continued, although with somewhat greater error in (d). Taylor agrees with Mayne's conclusion in Reference 25 that the response "is not under closed loop control with the eyes included in the loop." Taylor says that the movement response is ballistic: the effectors react in open loop

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fashion to the signal from the central nervous system which was set during the reaction-time delay. Mayne points out that such an open loop response could not account for the oscillatory "hunting" which is apparent in some responses to step inputs, such as that in (b) or (c) of Figure 8. An oscillation of this sort could occur only if the dynamic portion of the response is made under closed loop control. If the eyes are not included in the loop, the feedback signal, which is continually subtracted from the "command" signal set in the cerebellum during the dead portion of the response, must come from the proprioceptive receptors in the effector which makes the response. Mayne also points out one objection which can be made: If the proprioceptive receptor were continually controlling the response, the relatively slow reaction time to proprioceptive stimuli would impose a considerable time delay on the proprioceptive feedback signal, and this lag in the feedback would not permit the accuracy and quickness of the dynamic portion of the response. To answer this objection, Mayne states that a reaction-time delay is not determined by the time required for sensory perception and transmission, but that it is used up mostly in computing and setting the signal sent to the effector if a computation and setting up of the response are not required, the time delay imposed on the feedback signal may be very small. (In connection with this, it is known that the receptors in the retina can respond in about .01 second, yet the fastest reaction times for responses to visual stimuli are just under .2 second.) The essential hypothesis Mayne offers is that the dynamic portion of the response to a step input is made under closed loop control with the proprioceptive senses and without reaction-time delay.

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In an attempt to derive a linear transfer function which would describe the dynamic portion of the response, curves were closely fitted to typical responses to step inputs. Then the Laplace transform of the function representing the fitted curve was taken, multiplied by s (because the input was a step function), and divided by the magnitude of the step; the result is an approximation to the transfer function of the subject in responding to a step function. This work is described in detail in References 9, 21, and 25.

Figure 9, taken from Reference 25, shows a curve fitted to a typical response. A typical example from the same source is the following (see Figure 9 for an explanation of the notation used):

The function represented by the fitted curve is

$$\frac{x_o(t)}{X_i} = .95 + e^{-9t} - 3.2e^{-15t} + 95e^{-40.4t} + .434e^{-8.2t} \sin(39.7t + 47^\circ)$$

Therefore,

$$\frac{x_o(s)}{X_i} = \frac{.336(s^5 + 83.3s^4 - 1566s^3 - 76,650s^2 + 3.606 \times 10^6 s + 1.969 \times 10^7)}{s(s+7)(s+15)(s+40.4)(s^2 + 16.4s + 1642)}$$

Because the input, $X_i(t)$, is a step of magnitude $\underline{X_i}$, its Laplace transform is

$$X_i(s) = \frac{\underline{X_i}}{s}$$

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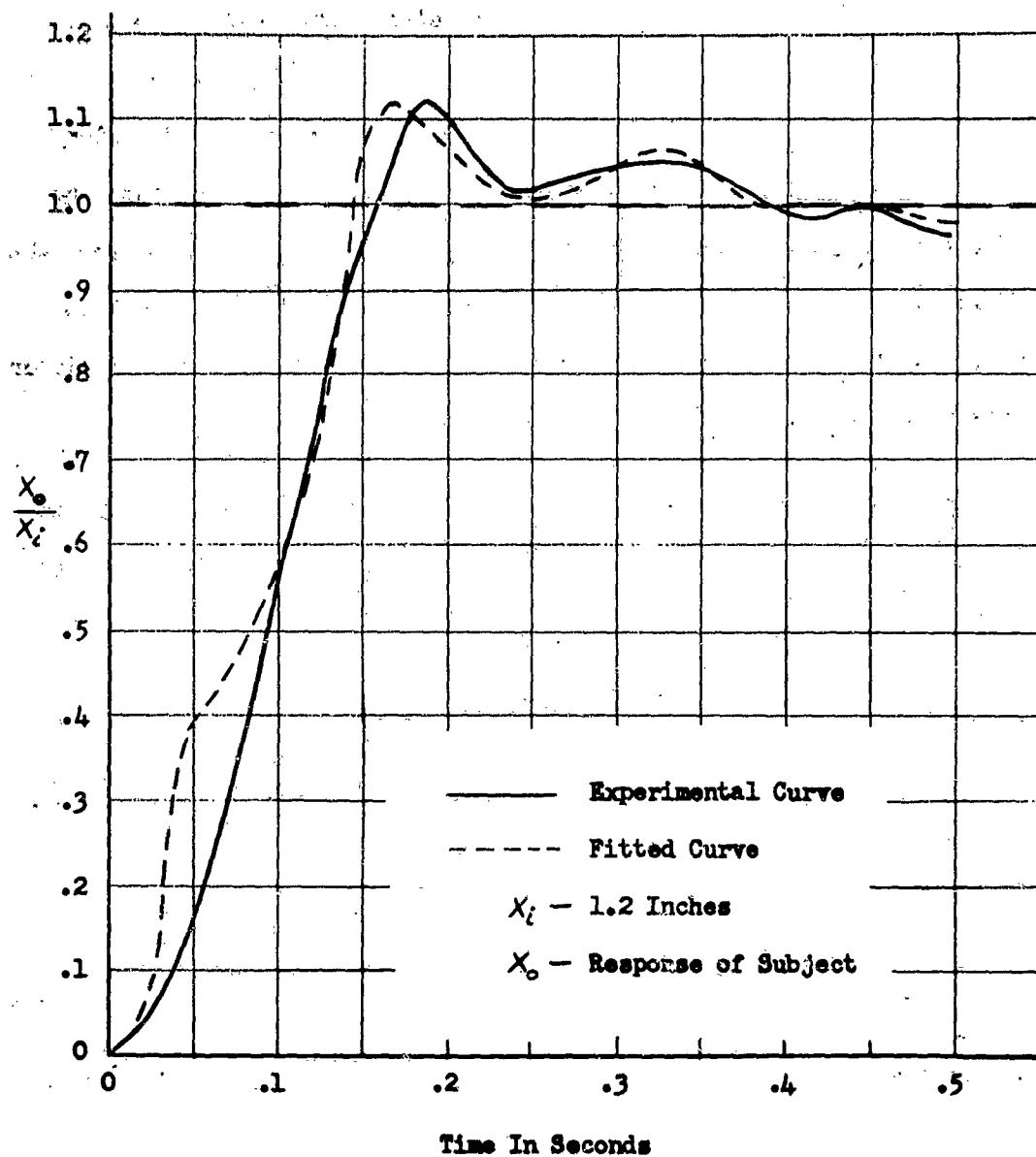


Figure 9. Dynamic Portion of the Response of a Subject to a Step Input of 1.2 Inches with Reaction-Time Delay Omitted (Reference 25)

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In this case, \bar{X}_i is 1.2, and the transfer function is

$$\frac{X_o(s)}{\bar{X}_i(s)} = \frac{.336(s^5 + .833s^4 - 1566s^3 - 76,650s^2 + 3.606 \times 10^4 s + 1.969 \times 10^7)}{s(s+7)(s+15)(s+40.4)(s^2 + 16.4s + 1642)}$$

Other transfer functions, similarly derived, and given in Reference 9, are

$$\frac{X_o(s)}{X_i(s)} = \frac{3.7(s^4 - 12/s^3 + 13,514s^2 - 6.44 \times 10^5 s + 1.9351 \times 10^7)}{(s+14)(s^2 + 25s + 832)(s^2 + 16s + 6140)} \quad (1)$$

and

$$\frac{X_o(s)}{X_i(s)} = \frac{-142(s - 92.6)(s + 1.4)(s^2 - 49.9s + 3963)}{(s+15.4)(s+7.3)(s^2 + 24.6s + 727)(s^2 + 13s + 2601)} \quad (2)$$

These are, of course, the closed loop transfer functions for the operator's response. For frequencies up to 20 rad/sec, the Nyquist plots of Equations (1) and (2) are matched by the plots obtained by closing the loop around the function

$$KG(s) = \frac{K}{s(T^2s^2 + 2ZTs + 1)} \quad (3)$$

where

$$T = .042$$

$$Z = .5$$

$$K = \begin{cases} 6.84 & \text{for Equation (1)} \\ 7.05 & \text{for Equation (2)} \end{cases}$$

Reference 9 contains these Nyquist plots.

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On the basis of agreement in Nyquist plots, it is suggested that the following transfer function describes the dynamic portion of the response of a human operator to a step input:

$$H(s) = \frac{KG(s)}{1 + KG(s)} \quad (4)$$

where $KG(s)$ is the function given in Equation (3).

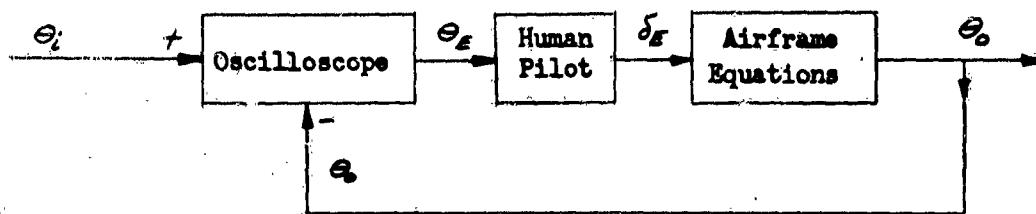
To include the dead portion of the response due to reaction-time delay, a factor $e^{-\tau s}$, where τ is the appropriate simple reaction time, must be included. This gives

$$e^{-\tau s} H(s) = \frac{KG(s)}{1 + KG(s)} e^{-\tau s} = \frac{e^{-\tau s}}{\frac{T^2 s^3}{K} + \frac{T s^2}{K} + \frac{s}{K} + 1} \quad (5)$$

To check this transfer function, a cockpit mockup was set up in conjunction with an analog computer which solved the longitudinal equations of motion for an F-89 airplane. In the mockup, an oscilloscope was used to simulate an artificial horizon; the pilot's stick in the mockup was provided with a variation of stick force with stick deflection. By moving the stick, trained pilots produced a voltage which represented elevator deflection,

δ_e , in the airframe dynamics as set up on the computer. A block diagram is given in Figure 10.

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θ_i is a step disturbance in pitch

θ_o is the pitch angle of the aircraft

$$\theta_e = \theta_i - \theta_o$$

Figure 10. Block Diagram Illustrating Cockpit Mockup and Analog Computer Installation Used to Determine Pilot Response to a Step-Disturbance in Pitch

Records of δ_e and θ_o were made for various step inputs.

The experiment was then repeated using a computer representation of the transfer function $H(s)$ in place of actual human beings. Since, according to the Goodyear studies, the pilot's response to such a step disturbance is not under continuous visual control but rather is made on the basis of a single quick observation and then carried out in closed loop fashion through the proprioceptive senses, it is very important to note that the step input, θ_i , and not the instantaneous error, θ_e , is fed to the function $e^{-Ts}H(s)$. Note the block diagram given in Figure 11. Here again the δ_e and θ_o obtained were recorded. The two traces for δ_e and θ_o thus obtained could be made to match very closely by simply varying the gain K between the

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values 6 and 10, which indicates the suitability of this transfer function for predicting responses of this type.

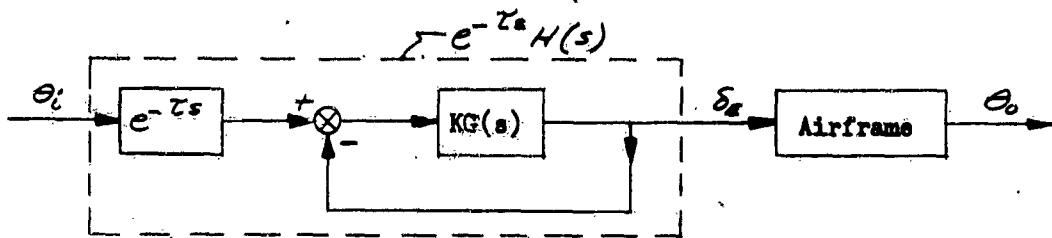


Figure 11. Block Diagram Illustrating an Analog Computer Installation Used to Check the Approximate Transfer Function Obtained by Closing the Loop Around $KG(s)$ of Equation (3)

It is worthwhile to mention the possibility of approximating $e^{-\tau s} H(s)$ by omitting terms with second and higher powers of s . This would yield

$$e^{-\tau s} H(s) \approx \frac{e^{-\tau s}}{\frac{s}{K} + 1} \quad (6)$$

which is a good approximation at low frequencies.

In studying gunlaying problems under the assumption that the gunner's response is under continual visual control using the displayed error between target and gun positions, Ragazzini used the transfer function of Equation (7). In the control systems he studied, gun position was proportional to the operator's output which was a handle position (see Figure 12).

$$H(s) = \frac{d}{s} e^{-\tau s} \quad (7)$$

It must be pointed out that in Equation (7) $H(s)$ is the ratio of the operator's output, ϕ , to the error, θ_e , between the target position and the gun position, as is required by the assumption at the beginning of this paragraph.

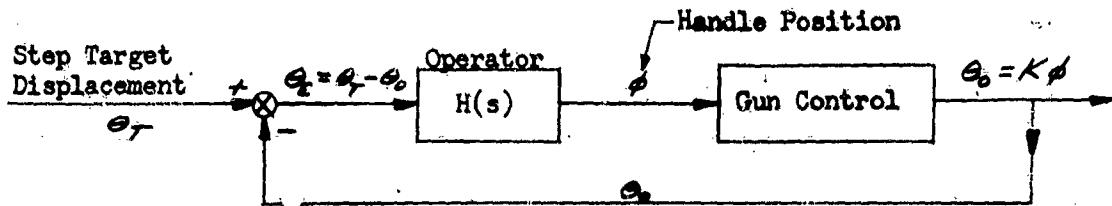


Figure 12. Block Diagram Illustrating the Type of Gun-Control Problem in Which the Transfer Function of Equation (7) Was Used to Represent the Gunner

SECTION 3 - THE OPERATOR'S RESPONSE TO A SEQUENCE OF STEPS

For the simple case in which the sequence of steps comprises a square wave, the operator's response, as indicated in experiments conducted at Goodyear and reported in Reference 26, is analogous to his response to a simple sinusoid (see below). First there is a period during which reaction-time delay is apparent, and then a synchronous response is developed in which no lag exists between the steps and the operator's responses. This is at least true when the steps are spaced sufficiently far apart. The Goodyear study's explanation of this type of response is the same as that for the response to a sine wave, and is presented in Section 4 of this chapter.

What of the operator's response when the sequence is irregular, so that because of uneven intervals between steps and/or of varying amplitude, the factors of prediction and learning are excluded for the most part, and the response must be under continuous control of the external senses? It

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has already been pointed out (see the discussion of reaction time, Section 4 of this chapter) that several investigators, among them Hick (Reference 11) and Vince (Reference 31), believe that a psychological refractory phase (analogous to the refractory phase for individual nerves and muscle fibers) exists, and that a certain minimum time must therefore elapse after a first response before the response to a second stimulus can be made. This is in addition to the normal reaction-time delay which would be expected to separate the second stimulus and response. However, other investigators, notably Ellson in Reference 8, have performed experiments from which it is possible to infer that no such phase exists.

The importance of this point is as follows: It would be convenient if we could apply the principle of superposition and predict the response of a human operator to an irregular sequence of steps simply as the resultant of his responses to the individual steps, the latter responses being obtained from the transfer function for step-function responses derived above. Put in another way, it would be convenient if in a computer study the transfer function $H(s)$ of Equation (6) could be used to represent the human operator's response to an unpredictable sequence of steps as well as to a single step. What this question amounts to is: Can we assume that the operator's response obeys the principle of superposition, at least in relating the response to an irregular sequence of steps with the response to a single step? If there is a refractory phase, the answer is no, because when the steps of the sequence are close enough together, the operator's response will be intermittent and not

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simply the resultant of the responses to each step. On the other hand, superposition can be applied to the response to an irregular sequence if there is no refractory phase, provided of course that prediction is eliminated by the irregularity of the sequence.

Ellson's conclusion that there is no refractory phase in the response to a sequence of opposed steps of constant amplitude seems to be valid. The experiment and its conclusions are so elegant and its significance so great that it will be described in detail below, as reported by Ellson in Reference 8.

The assumption of the existence of a refractory phase is equivalent to what Ellson calls Hypothesis I; he also formulates an alternative Hypothesis II, which contradicts the former. From each he draws certain conclusions which are checked against the results of a very carefully conducted experiment involving a tracking problem. He found that the conclusions from Hypothesis I are contradicted, but that those from Hypothesis II are essentially in agreement with experimental results although there are slight discrepancies. Hypothesis II is therefore closer to the truth. The hypotheses and their conclusions are presented below.

HYPOTHESIS I: When the interval between two opposed step-function stimuli is so short that the normal responses would overlap in time, the beginning of the second response will be delayed until the first is completed.

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Conclusions

A. Reaction Time

1. The reaction time for the first response, RT_1 , should not vary as a function of the interval between stimuli.
2. The reaction time for the second response, RT_2 , at the shorter intervals, should be increased over its normal value, and should satisfy

$$RT_2 \geq RT_{n_1} + MT_{n_1} - i$$

where RT_{n_1} is the normal reaction time of the first response
 MT_{n_1} is the normal movement time for the first response
 i is the interval between steps

To establish this inequality, let the first and second stimuli start respectively at times t_{10} and t_{20} . Let the first and second responses start at t_{11} and t_{21} . Let t_{12} be the time that the first response ends.

Then

$$RT_1 = t_{11} - t_{10}$$

$$MT_1 = t_{12} - t_{11}$$

$$i = t_{20} - t_{10}$$

$$RT_2 = t_{21} - t_{20}$$

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Then--

$$RT_1 + MT_1 - i = t_{12} - t_{20}$$

The assumption of a refractory phase means that

$$t_{21} \geq t_{12}$$

Therefore, it implies that

$$RT_2 \geq RT_1 + MT_1 - i$$

B. The Movement Times, MT_1 and MT_2 , should both be independent of the interval between stimuli.

C. The Amplitudes, A_1 and A_2 , of the two responses should be independent of the interval.

HYPOTHESIS II: When the interval between two opposed step-function stimuli is so short that the normal responses to the respective stimuli would overlap in time, the actual movement will be the resultant obtained by taking the algebraic sum of the two responses.

Conclusions

A. Reaction Time

1. RT_1 should not vary.
2. RT_2 is not measurable under the assumptions of Hypothesis II. For this hypothesis, RT_2 is defined to be the time between the second stimulus and the beginning of the apparent

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return movement. It should increase as i decreases.

B. Movement Time

1. MT_1 should decrease as the interval, i , does (here MT_1 is time to beginning of return movement).
2. MT_2 should increase as MT_1 does.

C. Amplitude

1. The amplitude of the first response (height of peak) should decrease as the interval, i , does.
2. $A_2 = A_1$ if the second movement is a return to original position.

A careful experiment was conducted in which opposed steps at different intervals were responded to by 30 subjects. The presentation of the various intervals was random. Each subject had 10 trials at each interval.

Specific disagreements with the conclusions of Hypothesis I were:

1. Although RT_2 decreases as the interval does, it was always less than the predicted minimum. For the three shortest intervals (.05 second, .1 second, and .2 second), the difference between the predicted minimum and the RT_2 was statistically significant at the 1% level.
2. MT_1 does not remain constant, but decreases as the interval

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does. The difference between the mean movement time and MT_1 is statistically significant for the four shortest intervals (from .05 to .3 second), $p = .01$.

3. The amplitude of the first response decreases with decreasing interval size (except for the shortest interval, .05 second). For every interval from .05 to .4 second, the amplitude was significantly different from normal ($p = .01$).

Table XXXII summarizes the results.

Hypothesis I

Interval	RT_2		MT_1		A_1 (%)	
	Predicted	Obtained	Predicted	Obtained	Predicted	Obtained
.05	.414	.365	.236	.179	100	65.5
.10	.364	.358	.236	.182	100	57.6
.20	.264	.279	.236	.209	100	89.5

Hypothesis II

.05	.348	.365	.165	.179	55.5	65.5
.10	.315	.358	.187	.182	79.1	57.6
.20	.259	.279	.232	2.09	99.0	89.5

Table XXXII. Results of an Experiment to Check the Conclusions from Ellson's Hypotheses I and II (Ellson, Reference 8)

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The author states that the results of the experiment are significantly different statistically from the conclusions of Hypothesis I in six out of nine predictions (the exceptions being the R_2^T for .1 and .2 second, and A , for .2 second intervals). In two cases, the predictions based on Hypothesis II (R_2^T and A , for .1 second) are significantly in error (but Ellison had reason to believe that this was due to an experimental error which could be eliminated).

Although Hypothesis II is not definitely proved to be correct, Hypothesis I appears to be discredited on the basis of this experiment. Hypothesis II may be used until more definite information is established. In effect, it states that superposition can be applied to unpredictable sequences of step functions and can be used, with caution, to obtain the response to such sequences from the response to a single step function. If this is so, the response to an irregular, unpredictable sequence of steps can be obtained from the transfer function $H(s)$. In the case of certain sequences of steps, the operator's response may be adversely affected by a significant nonlinearity, called the range-effect, which is caused by faulty prediction. Given a sequence of steps of the same relative size, a subject will tend to overestimate his response to a smaller step and underestimate his response to a larger one. What happens may be that he sets in a learned response based on the preceding steps even though it is an incorrect response.

Section 4

SECTION 4 - THE OPERATOR'S RESPONSE TO A SIMPLE SINE WAVE

Figure 13, taken from the Goodyear studies, illustrates a typical feature of a human operator's response to a simple sine-wave input of fairly low frequency; i.e., the response seems to occur in two parts, as pointed out by Mayne in Reference 25.

1. Initially, there is a phase lag, but the lag is too short to be due to a reaction-time delay (a factor of $e^{-\zeta s}$ would give a phase lag of 90° at a frequency of 1 cps if ζ is taken to be .25).
2. Very shortly, the response changes to a synchronous following of the sine wave with no phase lag and only slight attenuation.

The proposed explanation of these characteristics, as given in the Goodyear studies, References 9 and 25, is summarized below. The first portion of the response occurs when the operator is under closed loop control continually, with the eyes included in the loop. Since the eyes are exercising continuous control, no time is required for computation and setting of responses in the cerebellum (see the discussion of the response to a step function), and since, in Mayne's view, such time is the chief factor in reaction-time delay, it would be possible to have this continuous control without the phase lag due to a reaction-time delay. (It should be pointed out here that in Reference 9 Mayne states that it was never possible to obtain such continuous control without reaction-time delay when complex inputs were used.)

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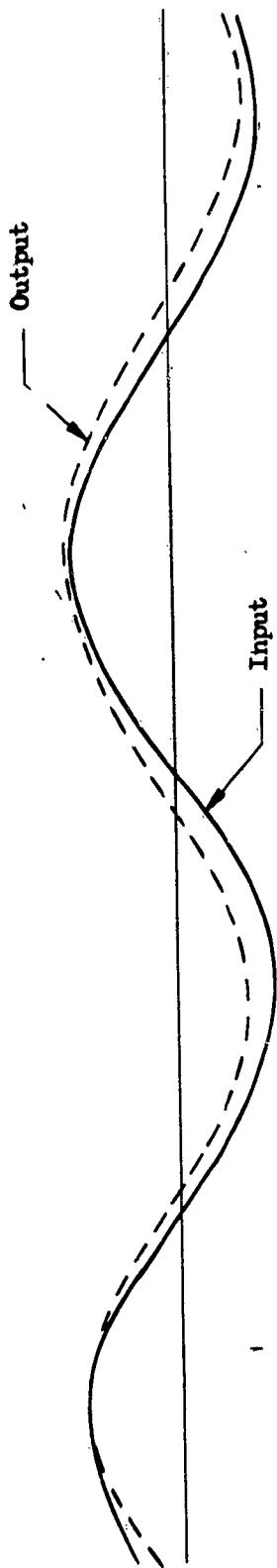
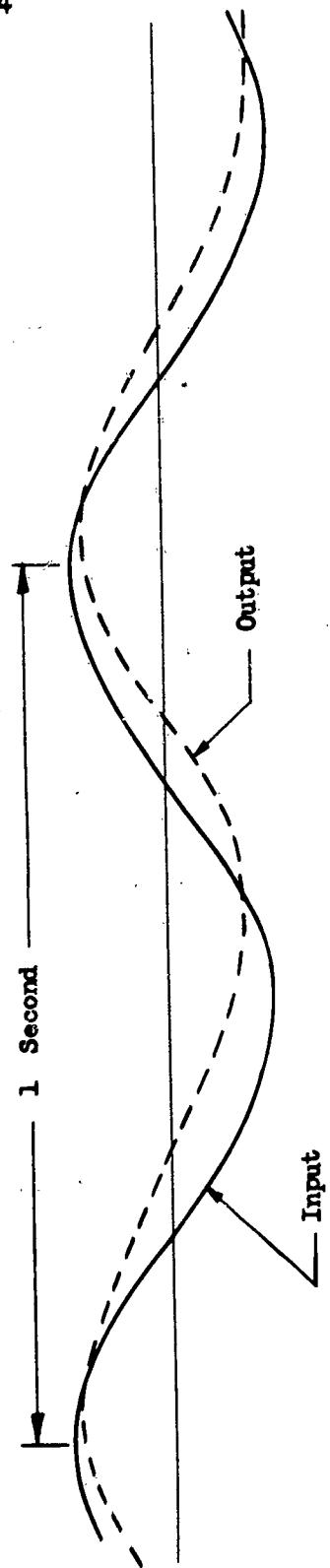


Figure 13. Typical Phases of the Response to a Simple Sinusoid (Reference 25)

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To accomplish the synchronous mode of response, the operator must have added some sort of prediction to his response to eliminate the phase lag entirely.

As explained above for step sequences, if the closed loop operation of a human being is linear, it should be possible to express his response to a sine wave by using his transfer function in response to a step input. Immediate objections make it clear that the over-all operation is not linear. In the first place, correlation between the synchronous portion and the response to a step is impossible because the absence of phase in the former would imply an instantaneous response to a step input. This never occurs.

It has been mentioned above that the initial portion of the response could not involve a fixed reaction-time delay since this imposes a 90° phase lag on a response to a sinusoid of 1 cps, whereas the observed phase lag seems to be only of the order of 40° . However, the response to a step function does include a reaction-time delay, and therefore the two responses cannot be reconciled. The foregoing argument is Mayne's. It does not answer the objection that the reaction-time phase lag of 90° may be offset by a prediction, made by the operator, and based on a rate signal which would introduce a phase lead of 90° . Such a prediction would be impossible in the response to a step function, and the phase lag due to reaction-time delay would be apparent in this type of response.

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In the synchronous mode, this partial prediction may be replaced by a learned rhythmic response after the pattern of the input has been perceived.

What Mayne suggests is that the dynamic portion of the response to a step function can be correlated with the initial portion of the response to a sine wave. In this connection, it is worth noting that the 40° phase lag observed in the response is approximately equal to the phase lag which would be caused by the transfer function $H(s)$ of Equation (7) at the frequency of 1 cps. The hypothesis is offered by Mayne that the nonsynchronous portion of the response to a sine wave is accomplished by a loop closed around the "neuromuscular" transfer function $KG(s)$ with the eyes providing the continuous feedback signal without reaction-time delay; the transfer function for the operator then would be the function $H(s)$ of Equation (6) during the nonsynchronous portion of the response to a sine wave, the same function being the transfer function for the dynamic portion of the response to a step input.

To check this hypothesis, a function with sine-wave components of three different frequencies was tracked by a human subject and his output recorded. The experiment was then repeated using an analog computer to represent the transfer function

$$\frac{KG(s)}{1+KG(s)}$$

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Figure 14 shows a comparison of the results; satisfactory agreement was achieved for the phase relationships, but not for the amplitudes; it is concluded by Mayne that an operator can respond to certain inputs, including oscillatory ones, in closed loop fashion, with the eyes included in the loop, and without reaction-time delay.

In connection with the synchronous mode, this type of response is also found in the response to a square wave. Such a response can be continued without the use of the eyes, once it has been started. Evidently, after training, the operator can "set in" to his effectors a certain range of functions which determine his response. The control of this response may or may not be made closed loop using the proprioceptive sense. The theory presented in the Goodyear reports would imply that it is.

SECTION 5 - THE OPERATOR'S RESPONSE TO RANDOM OR RANDOM-APPEARING INPUTS

Responses to complex inputs show a type of prediction which is called partial prediction in Reference 25. The nature of partial prediction is that it is a continuous operation performed on data continuously observed by the external senses. This property distinguishes it from total prediction which is observed only in response to simple functions, such as a step, or in the synchronous part of the response to a sine wave. Characteristic of total prediction is the fact that the external senses

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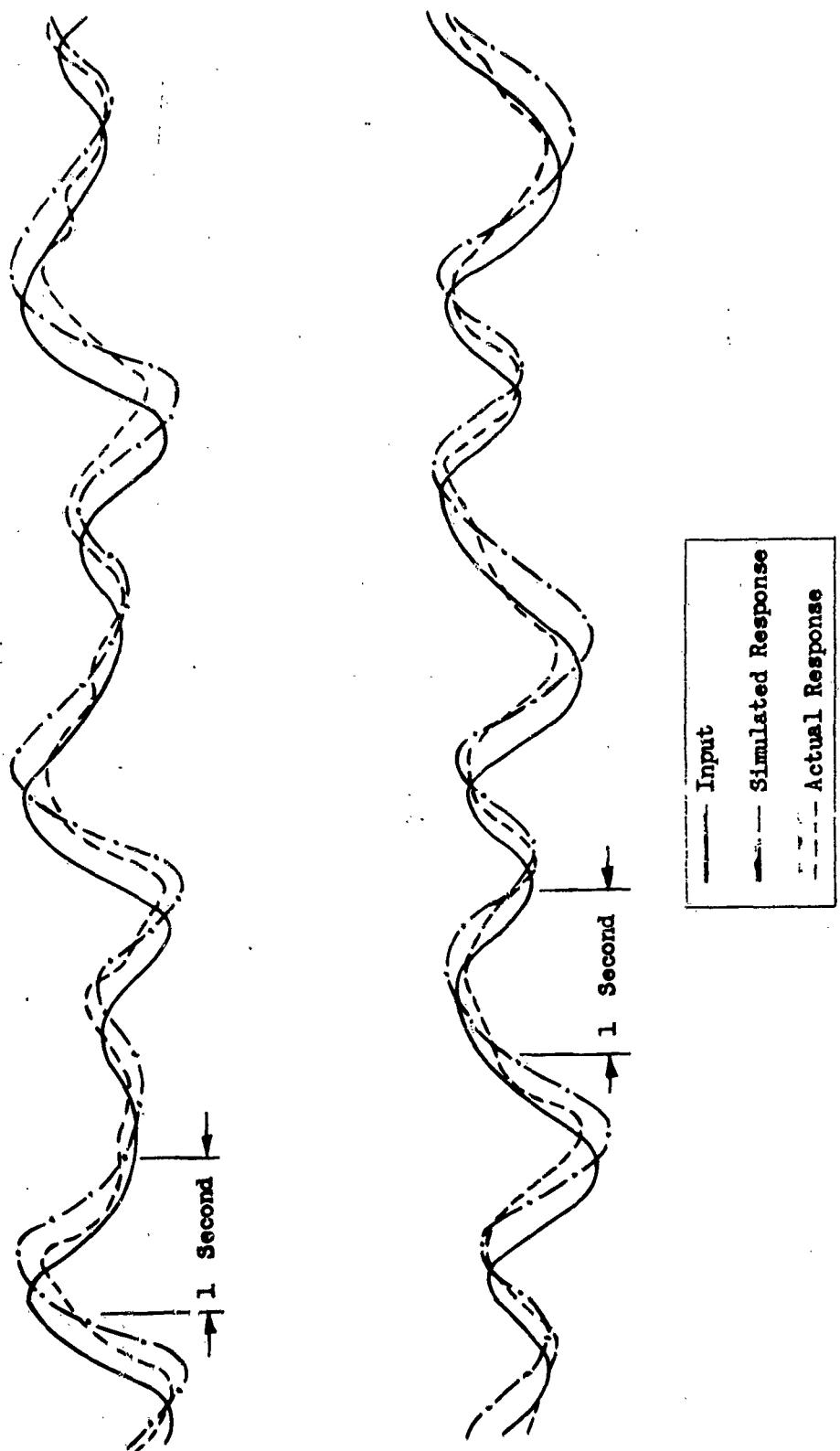


Figure 14. Response to Complex Input (Reference 25)

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are disconnected after a response has been set in the central nervous system to be carried out by the effectors, possibly under closed loop control of the proprioceptive senses. (If so, the prediction would have to include a phase lead in the case of a synchronous response to offset the phase lag due to the neuromuscular transfer function.) Intermittently, the external senses intervene to check the operation. Without such total prediction, where an entire response is pre-set in the neural centers, elementary skilled activities would be impossible since continuous control by the external senses cannot be exerted. Activities like throwing a ball, tying shoelaces in the dark, or catching a ball and tagging a base runner in one continuous motion are examples.

However, in responding to complex, unfamiliar inputs, total prediction cannot be applied, and partial prediction must be relied on. This may involve simple rate judgment of stimulus; or it may involve smoothing, where the operator relies on averaging out the error.

Another feature of responses to complex inputs is intermittency. According to Reference 9, it was never possible with complex inputs to obtain closed loop operation without a fixed reaction-time delay as was possible in the initial portion of the response to a sine wave. This dead time makes the operation intermittent when the input is complex enough to preclude total prediction.

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Tustin (Reference 30), North (Reference 22), and a Goodyear report (Reference 9) are all agreed that the operator's response to complex inputs cannot be described on a linear basis, but each takes a different approach as the result of this conclusion. In the Goodyear study, a nonlinear analog computer setup was derived, which was adjusted, as necessary, to represent a pilot in a cockpit mockup, controlling a simulated airplane. Tustin derives a "nearest linear law" to describe a gunlayer's response. North adds a stochastic term to a linear function to represent the pilot. These three approaches and some of the results are described below.

What was attempted in the Goodyear studies was to devise an analog computer setup which could simulate a pilot in conjunction with an analog computer representation of the longitudinal dynamics of an F-89. A complex function, with four sine-wave components, was used as a forcing function, θ_i , representing the pitching motion produced by gusts only, regardless of the effect of the controls. The error signal, θ_E , which was fed to the computer representation of the pilot, is then determined as the resultant of the gust effect, θ_i , and the pitch angle, θ , due to the elevator deflection produced to control the airplane. Preliminary studies were made in which trained pilots were used; the signal θ_E was displayed to them on an oscilloscope altered to resemble a gyro horizon. The pilots operated a control stick which was artificially provided with stick feel. Their responses to complex inputs were studied and later compared with the simulation responses. On the basis of these studies, it was felt that

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the simulator should include the following characteristics of the pilots' responses:

1. Rate Judgment. It was assumed than in controlling the pitch of an airplane, the pilot uses rate-of-pitch error.
2. Reaction-Time Delay. As mentioned above, it was never possible to observe closed loop operation with the external senses and complex inputs without this delay.
3. Rate Threshold. This threshold is much higher than the physiological threshold for visual perception of motion. Evidently, there is a threshold of indifference in which pilots deliberately neglect rates which they consider too small to bother with.
4. Clamping. Once a correction was made, pilots tended to "clamp" to this deflection until the pitch error approached zero.
5. Neuromuscular Lag. The second order lag was presented in Section 2 of this chapter as the transfer function for the dynamic portion of the response to a step input.

After preliminary tests, the neuromuscular lag was omitted from the simulator because its effect was negligible in comparison with the reaction-time delay. It was also found necessary to include a pitch-error

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signal as well as pitch-error rate; if this was not included, the airplane would slowly depart from trim, due to the rate threshold, even with no θ_i . For simplicity, a simple limiting was used instead of trying to simulate clamping. Finally, a lead-lag circuit instead of a pure lead was used to simulate rate judgment.

Figure 16 is a schematic diagram of the computer setup finally used, and Figure 15 presents a block diagram of it.

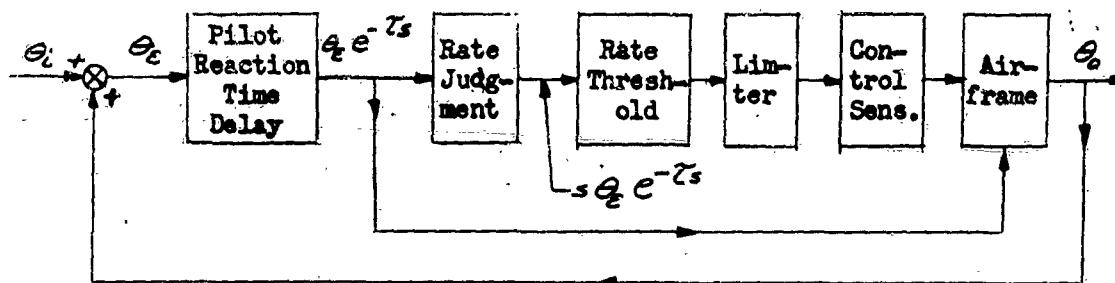


Figure 15. Block Diagram of the Analog Computer Installation Devised by Goodyear Aircraft, Inc., to Simulate a Human Pilot (Wiring Diagram Is Shown in Figure 16)

Figure 17 shows comparative results obtained from pilots and the simulator; the agreement was very good after suitable adjustment of the parameters, but these values are not given by Mayne.

Numerous investigators, among them Phillips (Reference 17), Hick and Bates (Reference 14), and Tustin (Reference 9) have used linear transfer functions with an added, fixed, reaction-time delay to represent the human operator of gun-aiming mechanisms. In such a situation, the operator

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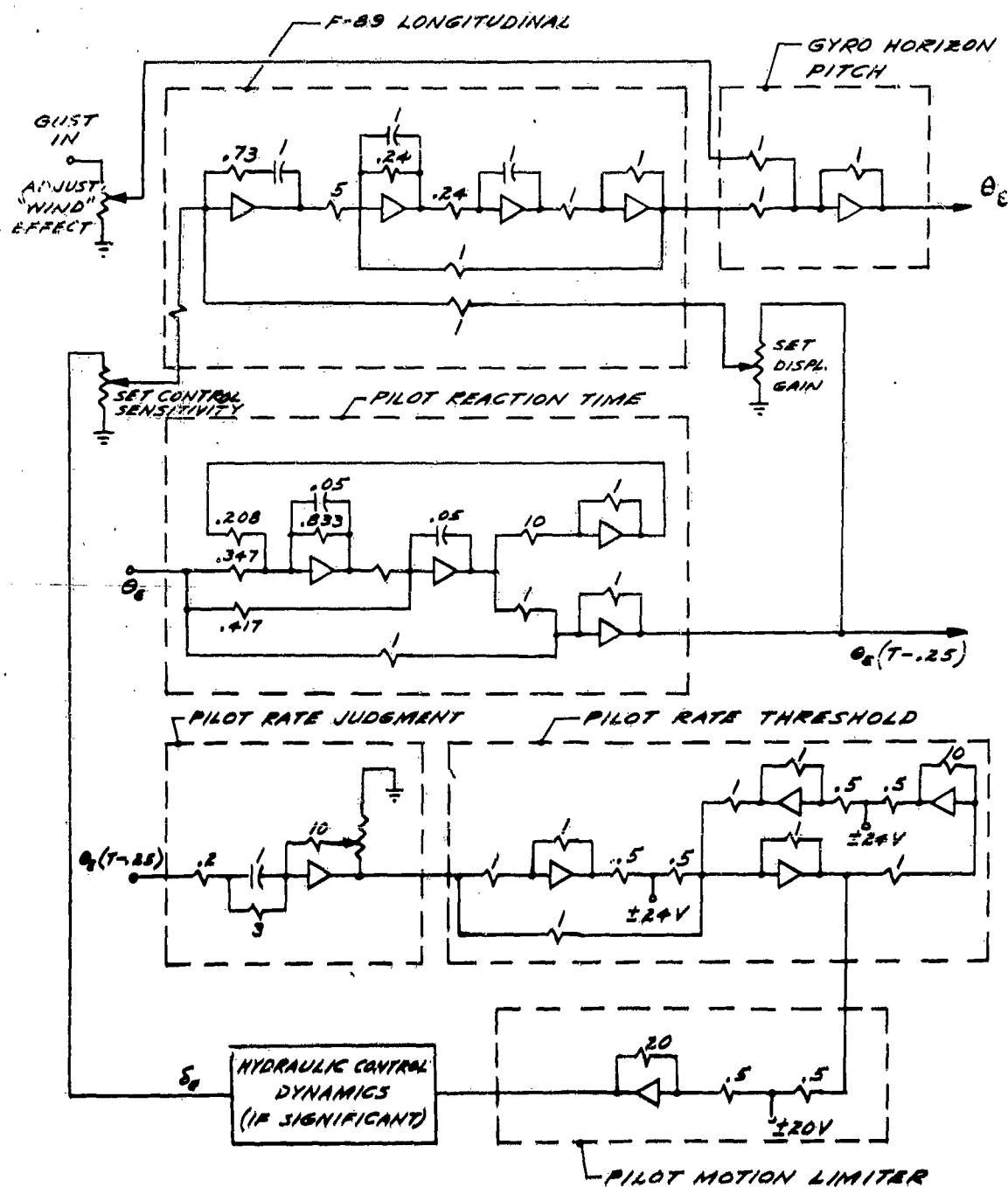


Figure 16. Analog Computer Schematic for Simulation of Pilot and Aircraft (Reference 9)

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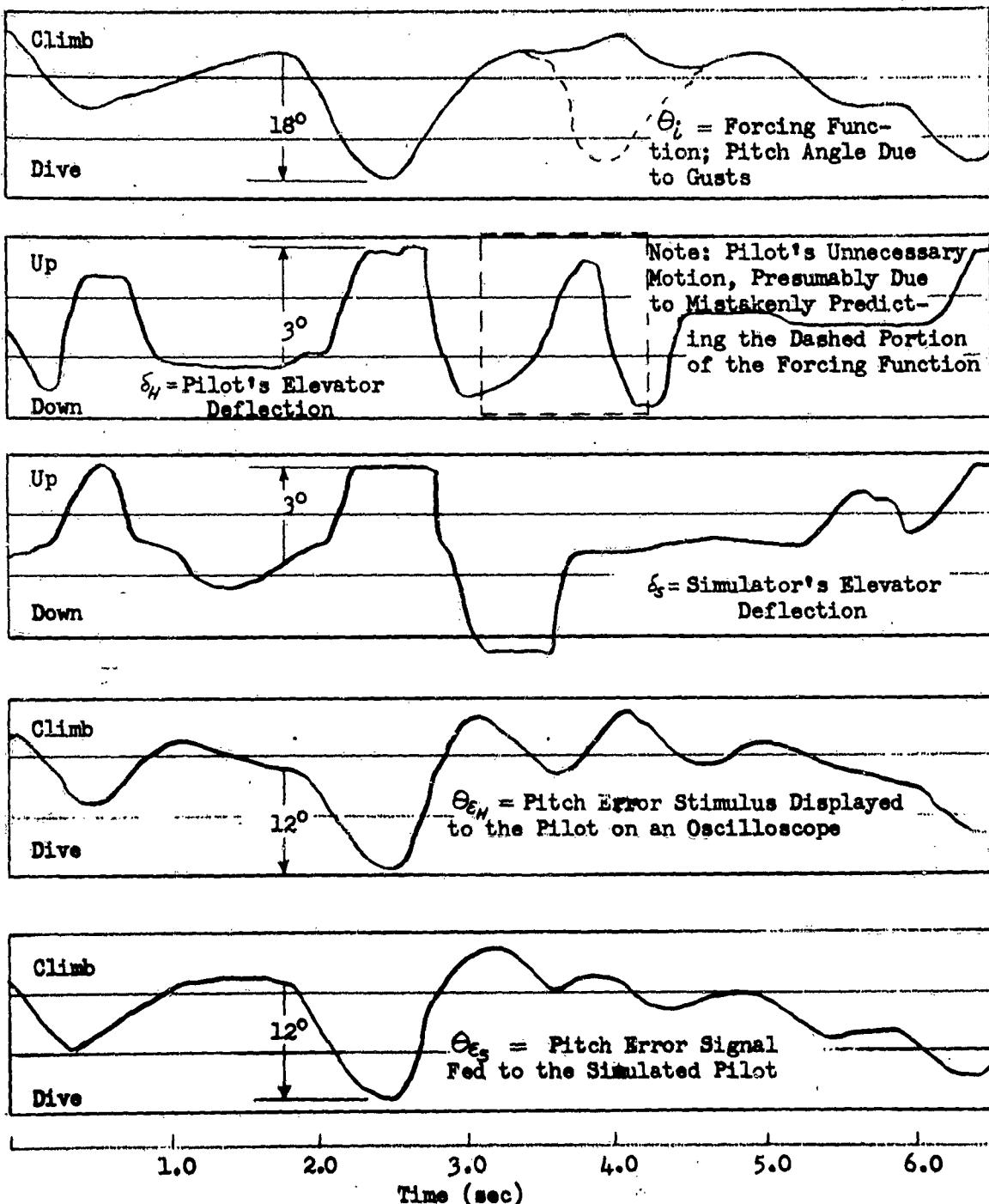


Figure 17. Record of Forcing Function and Responses from Both a Pilot and the Simulator of Figure 15 (Reference 9)

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is part of a system such as the one shown in block diagram form in Figure 18.

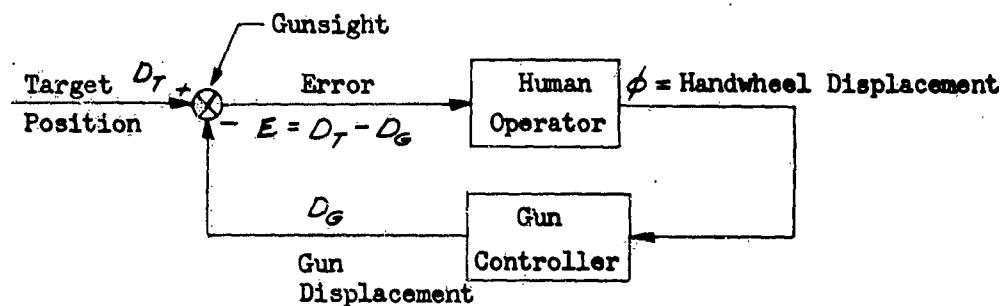


Figure 18. Block Diagram of a General Gun-Control Problem

It is agreed that the human operator's output is principally a rate of turn of the handwheel. All such writers agree on the following:

1. The operator, after training, uses the rate-of-error as well as the error to operate the controller.
2. There is a fixed reaction-time delay between the operator's output and the error signal.

In other words, the operator is acting in closed loop fashion with the visual sense always in the loop. In these references, any neuromuscular lag is omitted, in agreement with the Goodyear finding that it is negligible in comparison with the fixed reaction-time delay. The following transfer function, then, is used by these authors to approximate human operation:

$$\frac{s\phi}{\zeta} = (a + bs) e^{-Ts} \quad (8)$$

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The values of the parameters a , b , and T which were used, vary widely. Phillips uses $T=.5$; North uses $T=.3$. Different operators of course display different ratios b/a . The aim of these investigators was to define the characteristics of the gun controller mechanism so that, according to some criterion, the performance of the system would be optimum. Phillips was investigating controllers of the type specified by the following transfer function (the so-called rate-aided lay mechanism):

$$sD_G = K \left(\frac{1}{L} + s \right) \phi$$

With the criterion of minimizing the RMS error, it was desired to determine the optimum value of L using the above transfer function for the operator. It was possible to show that

1. If $b=0$, the best L is $L=5T$. Taking $T=.5$, this means that the best L is 2.5. This checks with the empirically determined optimum value of from 2 to 3.
2. If $b \neq 0$, the RMS error is minimum if $L=\frac{T}{b}$, $aT=2.25$, and $b=4$.

To show that appreciable agreement with actual tracking-results is obtained by using such a transfer function for the operator, Tustin gives the curves of Figure 19, in which, taking $T=.3$, both $(1+2.5s)E$ and $s\phi$ (.3 second later) were computed and plotted. He points out that the following nonlinear discrepancies occur at several points:

1. Time delay longer than .3 second

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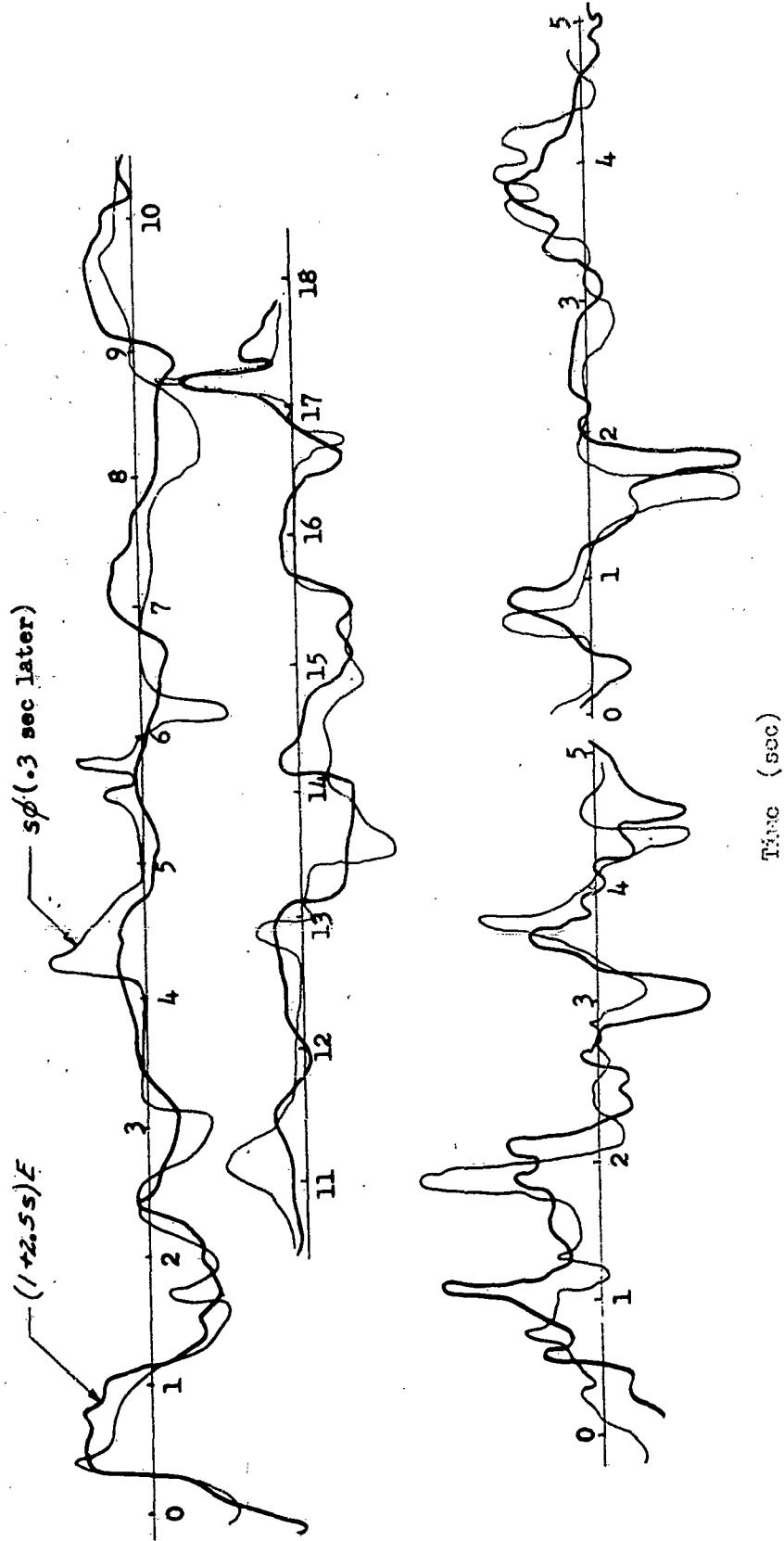


Figure 19. Plots Based on Actual Tracking Records to Show the Validity of the Transfer Function of Equation (6) with $a=1$, $b=2.5$, $T=.3$. If This Transfer Function Were Perfectly Correct, the Two Traces Would Coincide (Reference 29)

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2. Response stops although the stimulus continues (clamping)

3. Zero response for small or reversing stimuli (threshold)

It must be pointed out that both Tustin (Reference 30) and North (Reference 22) state specifically that the operator's response is not a linear function of the error, and to prove this statement, they show tracking records which indicate frequency components in ϕ and E which are different from those in the target displacement D_T . Tustin, however, shows that Equation (8) is about the closest linear approximation that can be obtained; actually, he says that the operator's output may not be just $s\phi$ but may also include handle displacement, in which case, Equation (8) should be

$$(k+s)\frac{\phi}{E} = (a+bs) e^{-Ts} \quad (9)$$

The operator's response consists of a random "jerkiness" superimposed on this response. North adds a stochastic term (completely random) to the operator's output as determined by Equation (1). Reference 22 is entirely devoted to an examination of the error produced by this term (using methods of statistics and spectral representation), and the variation of this stochastic error with parameters of the gun-control mechanism. Ellson, in a tracking experiment, used a pointer controlled by hand-grips from a standard gunmount to track another pointer; he found that the operator's response was most nearly linear (as determined by the phase and amplitude relations of the two pointers) when the input is

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most complex.* This is presumably due, as Mayne points out, to the inability to achieve total prediction. The operator falls back on partial prediction, which is probably simply using rate judgment, thus acting more like the first-order lead equalizer described in Equation (1).

In the course of an investigation into a certain type of dynamic instability of an aircraft, Phillips, Brown, and Matthews, in an NACA study, used the following function to represent a pilot's output (stick force, \bar{F}) in controlling the pitch angle, θ . Taking a reaction time of .2 second, they used

$$\frac{\bar{F}}{\theta} = 49 s e^{-2s}$$

They point out that according to Ellson's finding mentioned above, the pilot's response will be most nearly linear in such marginally stable systems which give nearly random inputs.

It was felt that the pitch angles were so small that the pilot could not sense them, and so no pitch displacement was included. Also, any muscular lag was omitted since it was felt that it would not produce any attenuation at the frequencies involved in this study. (The first order lag in the Goodyear transfer function would not cause any attenuation below 1 cps.) The gain, 49/lbs/rad/sec, was estimated by assuming

* D. G. Ellson and F. E. Gray, "Frequency Response of Human Operators Following a Sine Wave Input," USAF AMC, Aero-Medical Laboratory, Engineering Division, Report No. MCREXD 694-2N, Wright-Patterson Air Force Base, Dayton, Ohio, December 1948.

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that the pilot would use the same gain in controlling this undesirable pitch rate as he would to obtain the same pitch rate in a pull-up.

Cheatham, in Reference 4, describes an experiment conducted to determine the ability of pilots to control simulated unstable yawing oscillations and to determine the frequency response characteristics of pilots in controlling yawing or rolling oscillations. For this purpose, the pilots were seated in chairs which were caused to rotate about the appropriate axis, and controls were provided for exerting restoring moments on the chair. It was found that the ability of pilots to control an unstable yawing oscillation depends on all the following characteristics: the frequency and damping (negative) of the oscillation, the control effectiveness (measured by the yawing moment per unit rudder pedal deflection divided by the moment of inertia of the chair), and, in addition, the nature of the destabilizing moment, i.e., whether it was proportional to $\dot{\psi}$ or to $\int \dot{\psi} dt$. In the former, the pilot could stop the destabilizing moment by bringing the chair to rest in any position; in the latter, it was necessary to bring the chair back to the exact center to end the destabilizing moment. Although these results do not directly concern an approximate transfer function for the pilot's response, they are included in Figure 20 because they convey information about the response of the pilot in a lateral control problem. Figure 20 gives the controllability boundaries for controlling yawing oscillations. It is clear that pilots can control more divergent oscillations at higher frequencies if they can stabilize the

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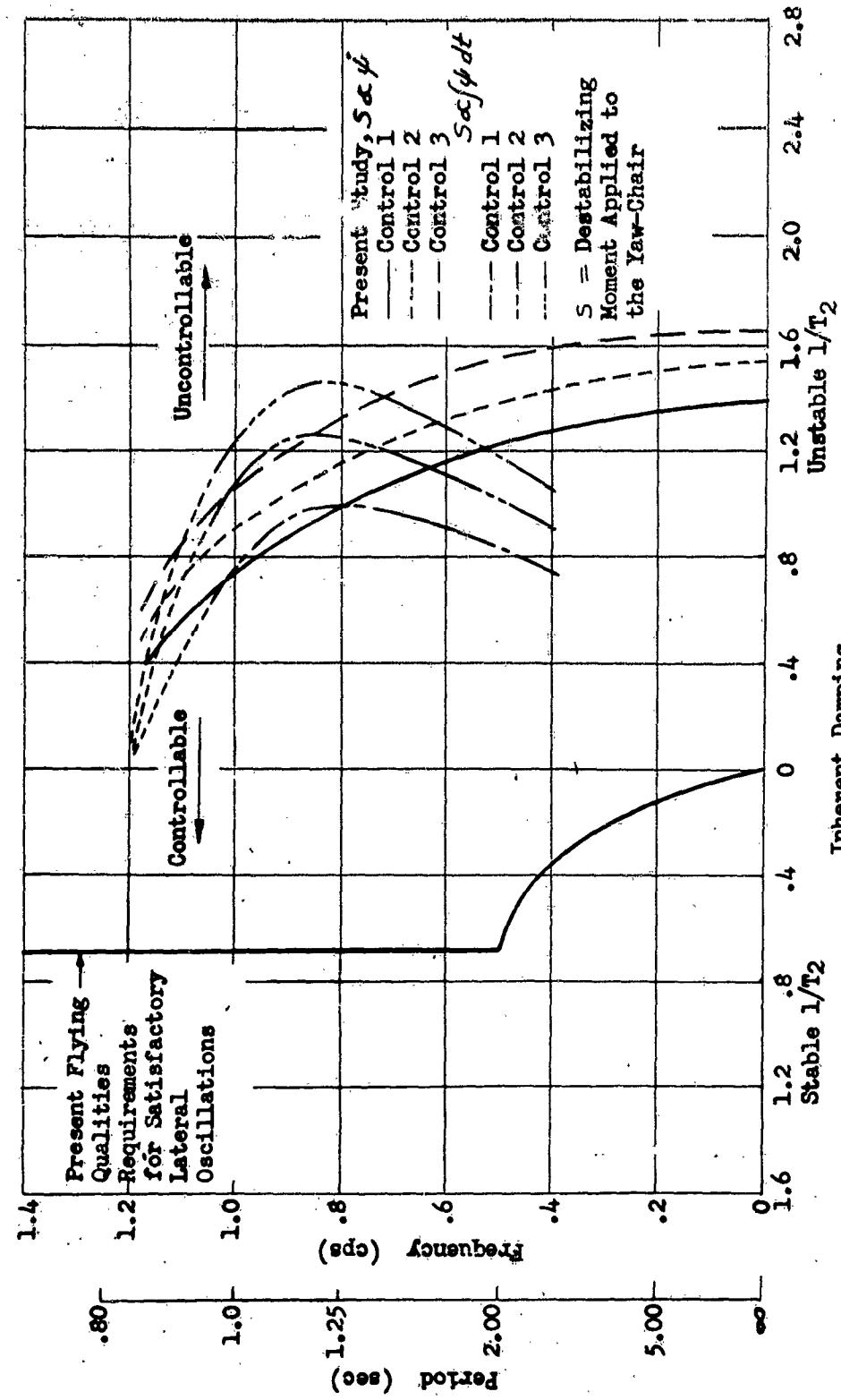


Figure 20. Boundaries of Pilot Ability to Control Simulated Aircraft Yawing Oscillations (Reference 4)

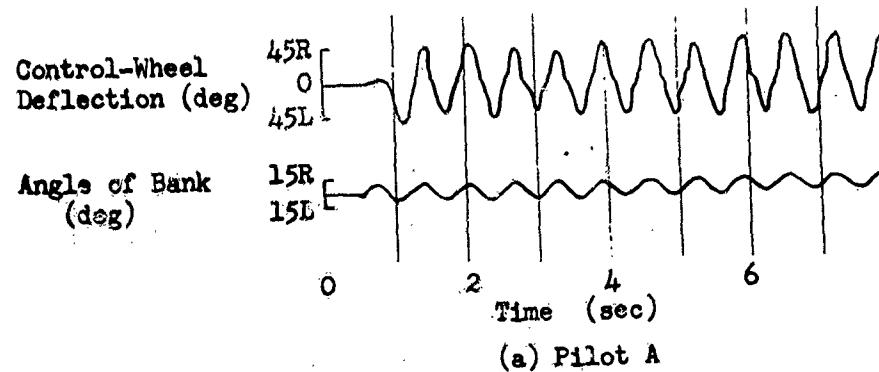
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motion by reducing yaw rate to zero than they can if they must maintain zero yaw error.

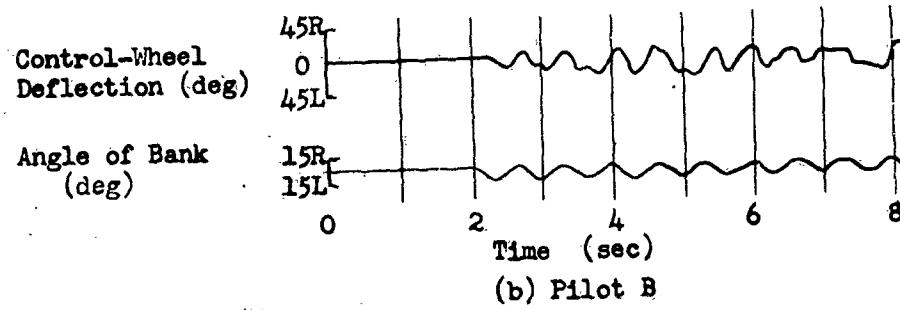
In determining the pilot control response characteristics, a rolling motion of the chair was used. Figure 21 shows three widely differing pilot responses to the same control problem, emphasizing again the wide variability in response from one individual to another, even among men of comparable training and skill. In (a), the pilot's response is the synchronous response described in the paragraphs above on response to simple sinusoids; the responses in (b) and (c) show no relation with such a synchronous mode. Figure 21(c) in particular indicates an intermittent response, the pilot evidently stopping his response from time to time to observe several cycles of the oscillation, presumably to determine a programmed response to set into his effectors. Figure 22 illustrates another specific characteristic, taken from yaw chair test records. Here the pilot quickly damps the oscillation but does not then decrease his control motion, whereas on a linear basis, the amplitude ratio of his control response to yawing displacement should be constant. Conspicuous also are the flat spots which may be signs of intermittency or the clamping observed by Mayne and North and mentioned above.

Cheatham concludes that it is useless to try to obtain frequency response characteristics of the pilot's response using forced sinusoidal oscillations. In the first place, since the pilots' controls had no effect on the forced oscillations, they could not tell when they were

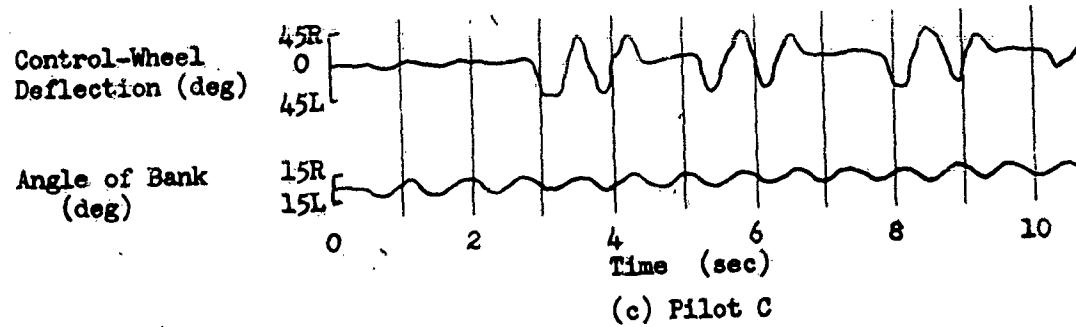
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(a) Pilot A



(b) Pilot B



(c) Pilot C

Figure 21. Control Response of Three Pilots to Forced Sinusoidal Rolling Oscillations. Approximate Frequency, 1.25 cps (Reference 4)

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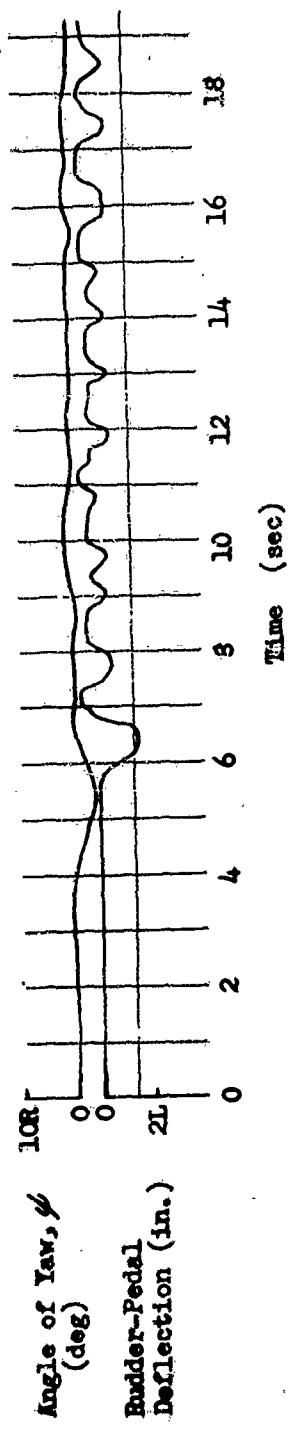


Figure 22. Test in Which the Pilot Shows a Type of Nonlinearity of Control Response (Reference 4)

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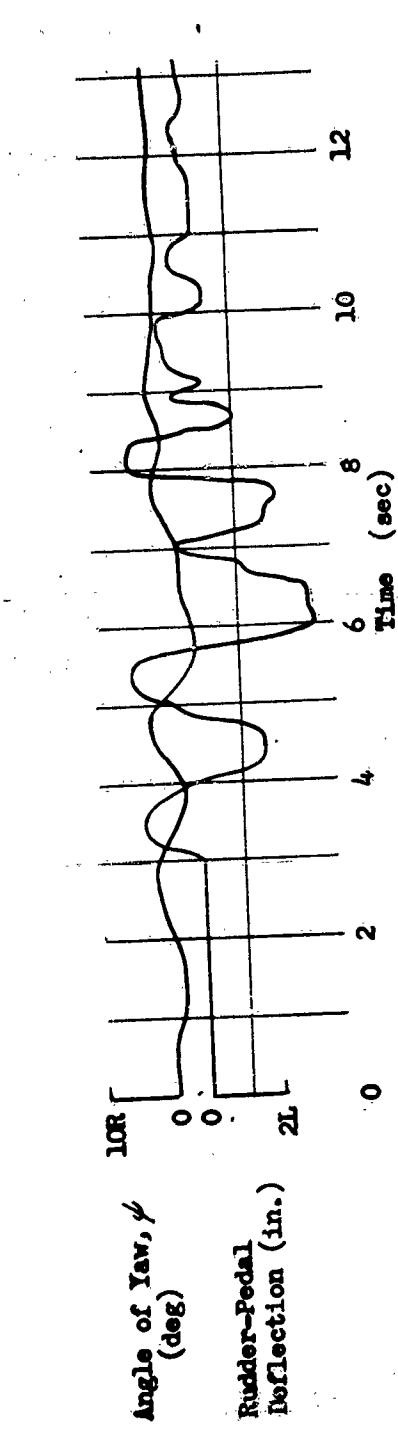
controlling effectively. This alters the response from normal. In the second place, the development of synchronous responses to sinusoidal inputs is a nonlinearity which has little significance for a frequency response which is to be applicable to a wide range of inputs.

Instead, the attempts to obtain the pilot's frequency response was made by harmonic analysis of marginally stable conditions of yawing oscillations. As shown in Figure 23, such conditions eliminate prediction as a factor in the operator's response, and their complex nature indicates that the response is most likely to be approximately linear, in accordance with Ellson's results quoted above. The results of the harmonic analysis indicate that a satisfactory expression of the operator's response is

$$\frac{\delta_R}{\psi} = .25 e^{-2s}$$

where δ_R is the operator's rudder pedal deflection and ψ is the yaw displacement. This approximation is especially significant because the pilot's stimulus was not visual alone, but also involved vestibular and proprioceptive perceptions of the rotation. There is one final non-linearity in the pilot's response which is worth noting. It seems that the pilot varies his gain, i.e., the ratio $|\delta_R/\psi|$, as the control effectiveness varies. Thus if N is the controlling moment in foot-pounds, it appears that $|\delta_R/\psi|$ is varied by the pilot to keep the product of $|\delta_R/\psi|$ and $|N/\delta_R|$ (the control effectiveness) approximately

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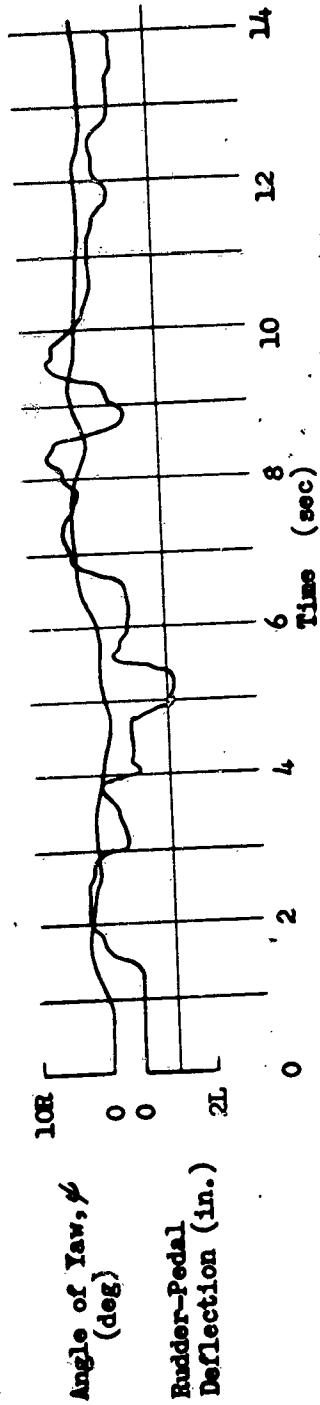


Figure 23. Examples of Yaw-Chair Records That Were Harmonically Analyzed to Determine Pilot Control Frequency Response to Simulated Aircraft Yawing Motion (Reference 4).

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constant. The response of the operator can therefore be expressed as

$$\frac{N}{\psi} = k s e^{-Ts}$$

where N/ψ is the control moment in foot-pounds

$$k = \left| \frac{s_R}{\dot{\psi}} \right| \cdot \left| \frac{N}{s_R} \right|$$

or, to include a first-order lag to account for neuromuscular factors,

$$\frac{N}{\psi} = \frac{k s e^{-Ts}}{1 + cs}$$

In conclusion, it should be mentioned that attempts have been made to obtain the pilot's frequency response from flight test data (see Reference 1). The data are dependent to a great extent upon

1. The aircraft used
2. The altitude of the flight
3. Mach number
4. Which control is being used, etc.

As Reference 1 points out, statistical studies of a large amount of such data might at least establish envelopes for frequency response characteristics; pilots whose performance fell within these envelopes could be considered as suitable for flying a certain type of aircraft.

It is hardly necessary to repeat that linear transfer functions, combined with reaction-time delays, do not suffice to describe the human

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operator's response. Furthermore, any approximation which is considered valid for a certain range of inputs in a certain problem must allow for a range of values of its parameters to account both for the individual-to-individual differences which must be expected and also for the differences in the same individual from time to time as his attention or concentration varies, or as he deliberately alters parameters such as his gain.

Nonetheless, it has been pointed out that responses to certain types of inputs can be usefully approximated by linear transfer functions combined with fixed reaction-time delays. Specifically,

Step Inputs. The Goodyear transfer function is a very good approximation to the operator's response in trying to follow a step displacement manually.

Sequences of Steps. Provided that the sequence is irregular enough to exclude prediction, the operator's response in following such a sequence can be assumed to be governed by the same transfer function as is his response to a single step (including the fixed reaction-time delay). If the sequence is regular, the response will be nonlinear; a very close following of the steps with very little lag is evidently made by a total prediction.

Sinusoid. The response very soon after the start becomes nonlinear in the sense that the operator by means of his

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prediction ability and rhythmic ability demonstrates almost exact following of the oscillation, at least for frequencies up to approximately 2 cps. This applies to manual tracking and to simulated airplane control problems.

Complex Inputs. Linear approximations to the operator's response have been successfully used both in visual tracking problems and in aircraft control studies. They are characterized by the following:

1. All involve rate perception by the operator, which means that the numerator has a term of the type $(a+bs)$. For small deviations occurring in flying where changes in load factor are the most important cue, the term a can be omitted.
2. All include a fixed reaction-time delay, i.e., a factor e^{-Ts} .

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